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Northeastern Chukchi Sea demersal fishes and associated environmental characteristics, 2009–2010

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ABSTRACT

Three closely-spaced study areas in the northeastern Chukchi Sea off of Alaska provided a opportunity to examine demersal fish communities over a small spatial scale as part of a multidisciplinary program. During 2009 and 2010, fishes in the three study areas (Klondike, Burger, and Statoil) were sampled at 37 stations with a plumb staff beam trawl and a 3 m beam trawl; 70% of stations were sampled during all three cruises. Fish catches were dominated by small fishes (< 150 mm TL), which cannot be wholly attributed to the small mesh size of the net. Output from generalized linear modeling of the data suggested that overall fish density, species richness, and density of Arctic staghorn sculpin (*Gymnocanthus tricuspis*) and Bering flounder (*Hippoglossoides robustus*) were higher in the more southerly Klondike study area than in the more northerly Burger and Statoil study areas. Arctic cod (*Boreogadus saida*) was abundant throughout the study region. Richness and density could be explained by the environmental variables that defined the overall study area. The Klondike study area was warmer and erosional in nature with higher proportions of gravel sediment. Other study areas were colder and more depositional in nature with muddier sediment and were characterized by high densities of megafaunal invertebrates such as brittle stars. There appeared to be a lack of ecological homogeneity across these three closely-spaced study areas of the Chukchi Sea.

1. Introduction

Baseline information about offshore ecosystems in the northeastern Chukchi Sea in general, and arctic marine fishes in particular, is sparse (Johnson, 1997; Power, 1997; Mecklenburg et al., 2002, 2008). There are no commercial fisheries in federal waters of the Alaskan arctic (Zeller et al., 2011), so baseline data cannot be reconstructed using historical commercial fisheries harvest data. At present, commercial fisheries for demersal fishes are prohibited in this area (North Pacific Fisheries Management Council (NPFMC), 2009), and mostly subsistence fishing in the region is limited to large pelagic fishes taken close to shore.

The entire Chukchi Sea is north of the regular fish-trawl research surveys conducted by NOAA Fisheries. Knowledge of the demersal fish communities in the Chukchi Sea comes from 23 scientific cruises in the eastern Chukchi Sea from 1959 to 2008. Since 1973, 16 cruises have collected fishes in the northeast Chukchi Sea at some stations north of 70°N. Unfortunately, these investigations used 15 different types of demersal trawls with headropes ranging from 3 m to 43 m and smallest mesh between 4 mm and 90 mm, which prohibits quantitative comparisons across studies (Norcross et al., 2013). The fishing gear used affects the number of fishes captured, however, the dominant fishes in the catch were comparable between recent (2004–2008; Norcross et al., 2013) and historical (1990–1991; Barber et al., 1997) collections. Over time Arctic cod (*Boreogadus saida*) was the most abundant demersal (Alverson and Wilimovsky, 1966; Frost and Lowry, 1983; Barber et al., 1997) and pelagic (Eisner et al., 2013) species. The same fish families dominated the northeast Chukchi throughout the historical collections (Norcross et al., 2013): cods (Gadidae), sculpins (Cottidae), eelpouts (Zoarcidae), and righteye flounders (Pleuronectidae).

Potential oil and gas exploration in US waters off Alaska has prompted interest in the overall ecology of the northeastern Chukchi Sea. The Chukchi is a shallow sea in the arctic bordered on the east by the Beaufort Sea and Alaskan coast, on the north by the Arctic Ocean, and on the south by the Bering Strait. Waters flow northward into the Chukchi Sea from the Bering Sea through Bering Strait. Renewed interest in this area provides the opportunity to fill longstanding gaps

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in understanding of the fish communities of the region. The Chukchi Sea Environmental Studies Program (CSESP) is an industry-sponsored comprehensive study (summarized by Day et al., 2013) focused around prospective development of three blocks (henceforth referred to as study areas) offshore in the Chukchi Sea (Fig. 1). Each study area has leases permitted to different companies with their own schedules for exploration. As such, the three study areas may experience differences with respect to the timing and severity of potential disturbances due to oil and gas development. Although there is nothing biologically significant about the boundaries circumscribing each study area, they represent logical partitions towards the facilitation of defining future disturbances and quantifying their effects.

Therefore our primary objective was to examine abundance of demersal fishes over the three closely-spaced study areas in the northeast Chukchi Sea by estimating and comparing descriptors of the fish community. Descriptors included species richness, total density, assemblage structure, and densities of five selected species, each of which represents a prominent family of fishes: Arctic cod (*B. saida*), Arctic staghorn sculpin (*Gymnocanthus tricuspis*), Canadian eelpout (*Lycodes polaris*), stout eelblenny (*Anisarchus medius*), and Bering flounder (*Hippoglossoides robustus*). Our initial expectation was that there would be little, if any, difference in the fish communities given their proximity.

Detecting changes in fish abundances can be confounded by environmental factors across space and time. Physical gradients are known to affect Chukchi fish communities over hundreds of kilometers (Barber et al., 1997; Norcross et al., 2011a, 2011b, 2013), but nothing is known about the effect over smaller spatial scales. Therefore our second objective was to relate any changes in the fish descriptor variables, if present, to physical gradients over the small, closely-spaced study areas.

Our third objective was to test for differences between two very similar types of trawls that were used in 2010. Examination of

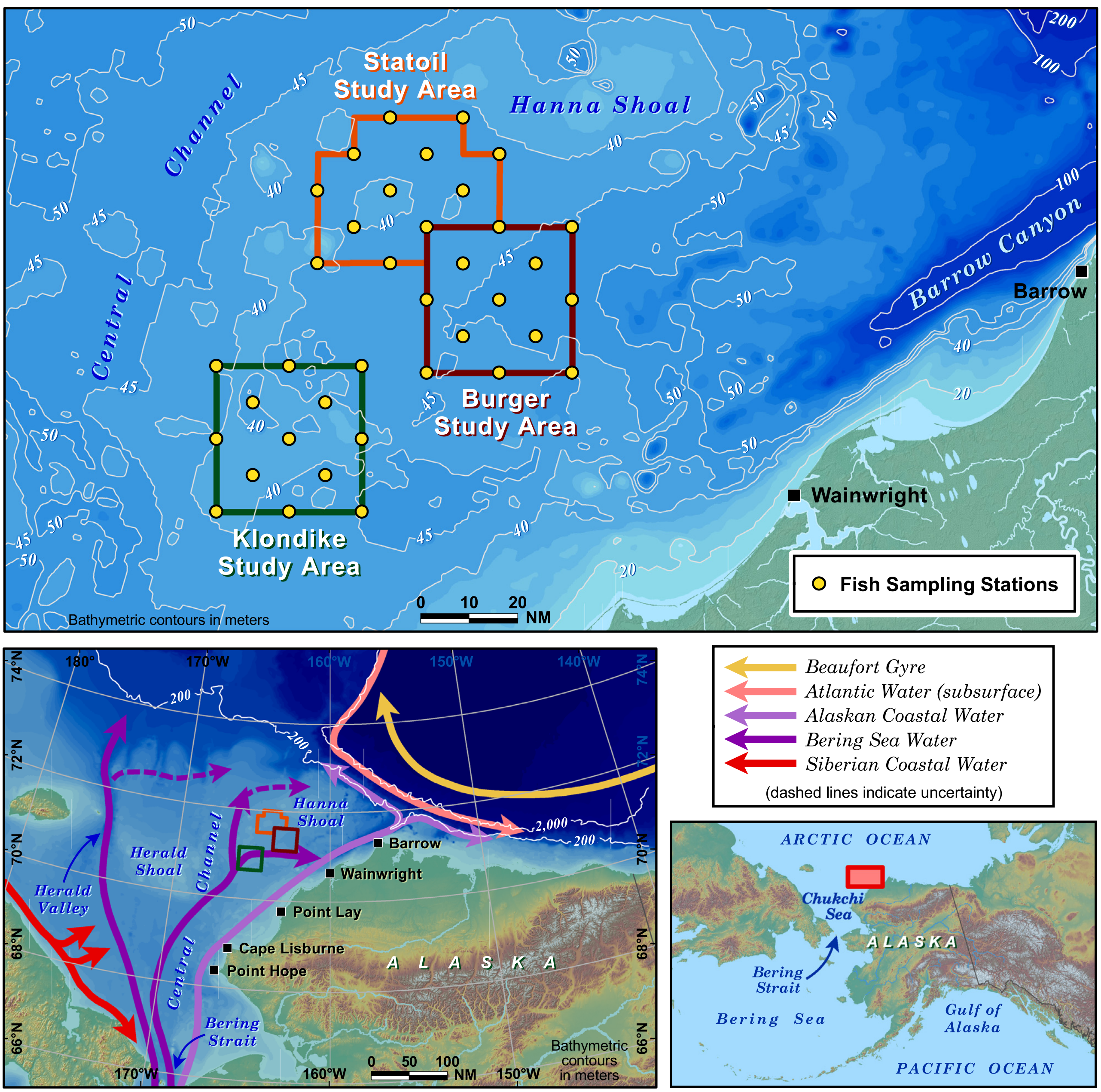

Fig. 1. Three study areas and stations sampled for fish in the northeastern Chukchi Sea, 2009–2010. The generalized direction of water flow in the indicated water masses is shown (modified from Weingartner et al., 2008).

historical fish data from the Chukchi Sea concluded that characterization of the demersal fish community was dependent upon type of gear used for collections (Norcross et al., 2013). Therefore, we examined catch differences between two gears whose efficiencies may have varied across species.

2. Study areas and methods

2.1. At-sea sampling

Three cruises in the northeastern Chukchi Sea contributed to the field collections made during this study: 23 July–18 August 2009, 22 September–12 October 2009, and 28 August–19 September 2010. We sampled two study areas (Klondike and Burger) during each of the 2009–2010 cruises and added a third area, Statoil, in 2010 (Fig. 1). Fish sampling occurred at predetermined stations arranged in a systematic, fixed grid within each study area. The Klondike and Burger study areas were identical in shape and size at ~55.6 × ~55.6 km (30 × 30 NM; Fig. 1). These two study areas were non-adjacent and centered about 70 km apart; the northeastern corner of Klondike was about 26 km from the southwestern corner of Burger. The Statoil study area was irregularly shaped, but covered about the same area (~3100 km^2) as each of the other two study areas, and adjoined the northwestern edge of the Burger study area. Stations were laid out in a grid with ~13.75 km (7.5 NM) spacing; Klondike and Burger each had 13 fixed stations and Statoil had 11 stations.

Environmental characteristics at each fish sampling station were assessed by other researchers of the CSESP. Vertical casts of a conductivity temperature density (CTD) instrument were conducted to assess bottom-water characteristics (Weingartner et al., 2013). Percent gravel, sand, and mud were assessed from sediment collected with a van Veen grab at each fishing station (Blanchard et al., this 2013a).

A 3 m plumb staff beam trawl (PSBT), modified from Gunderson and Ellis (1986), was used to collect demersal fishes in 2009 and 2010. Modifications included shortening the beam from 3.66 m to 3.05 m, seizing a lead-filled line to the foot rope and attaching 15 cm lengths of chain at 15 cm intervals along the foot rope, and lengthening the codend from 1 m to 4 m (Norcross et al., 2011a, 2011b). The net was rigged with a double tickler chain that consisted of a chain that was 0.5 m shorter than the foot rope and a second that was 0.9 m shorter than the foot rope. The effective mouth opening was 2.26 × 1.20 m. The net was 7 mm woven nylon netting with a 4 mm mesh codend liner. The PSBT was towed at < 2 kt on the bottom for ~3–5 min in 2009 and ~2–3 min in 2010, although there were instances in both years when it was towed for > 10 min. The PSBT was efficient at sampling the demersal fish community (Norcross et al., 1995), but was prone to fill with invertebrates and sediment, which limited the efficiency of processing tows of longer durations. The length of wire deployed was usually 2.5–3.5 times water depth. Bottom time was from when towing cable was completely deployed to start of haul back.

In tandem with fishing the PSBT, during 2010 we also fished a trawl that was designed to limit invertebrate and sediment accumulation at each station. The 3 m model 38 skate beam trawl (3mBT) consisted of a 5 m model 38 Skate Trawl fitted to a 3 m long tubular steel beam. The 3mBT had a 5 m head rope and a 6 m foot rope with 9 m of chain attached to the foot rope. The net was outfitted with a 12 mm mesh codend liner. To help keep the foot rope from digging into the bottom, the foot rope was equipped with 10 cm foam rollers. The vertical opening of the net was 1.0–1.5 m. The wing ends of the net were attached directly to the 3 m beam. The 3mBT was much less prone to filling with invertebrates and sediment than the PSBT, which allowed for tow times to be 15–30 min at < 2 kt.

Fish sampling was conducted aboard the 58 m long R/V Westward Wind, a converted king crab fishing and processing vessel. Gear deployment was limited to aft of the forecastle using a ship-mounted deck crane and a single trawl winch. Drag caused by the trawl and the forward location of the towing point caused the ship to slew to the right, which resulted in a curved tow track. Start time began when the appropriate amount of tow cable was deployed and stopped when retrieval of the cable began. Towing distance for each haul was calculated as a cumulative distance between each 10-s increment of tow time. The distance towed was multiplied by the width of the net mouth to get area fished at each station. This likely underestimated area sampled as the nets likely contacted the bottom before all of the tow cable was paid out. On one occasion during the August 2009 cruise, the PSBT catch was too large to bring aboard safely; approximately half of the haul was discarded overboard. To compensate, the catch quantified from half of the haul was doubled for this station.

At sea fishes were provisionally identified to the most specific taxonomic level possible using available guides (Matarese et al., 1989; Mecklenburg et al., 2002), counted and measured. Invertebrates in these collections are reported elsewhere (Blanchard et al., 2013b). A subsample of each species was subsequently examined onshore and identifications were finalized. Nomenclature follows the American Fisheries Society's publication of scientific and common names (Nelson et al., 2004) except for those species recognized after that publication (Mecklenburg et al., 2011). When a fish was broken into multiple pieces, only the head was counted to avoid duplicate counts. Total length (TL) of fishes was measured to the nearest mm.

2.2. Statistical methods for the univariate descriptors of the fish community

Dependent variables (i.e., univariate descriptors) included *Species richness*, *Total fish density*, and the numerical *densities* of Arctic cod, Arctic staghorn sculpin, Canadian eelpout, stout eelblenny and Bering flounder. By modeling *Species richness* on a per-1000 m^2 basis we could control for continuous increasing of richness with fishing effort (e.g., Lobo and Martin-Piera, 2002; O'Hara, 2005). *Density* values were reported per 1000 m^2. Objective 1 was to assess the inherent differences in these variables across the study areas and years. The model for Objective 1 was termed the environmentally naive (EN) model because no environmental data were included. The only independent variables were categorical: *Study Area*, *Year*, and *Gear*. *Gear* accounted for sampling efficiency varying between the two trawl types (Objective 3).

An environmentally informed (EI) model addressed Objective 2. In addition to the three categorical variables in the EN model, eight continuous variables were added to the EI model: *Depth*, *Bottom temperature*, *Bottom salinity*, *Percent gravel* in the substrate, *Percent mud* in the substrate, *Latitude* (north), *Longitude* (east), and *Distance offshore*. *Percent sand* was measured also but only two of the substrate variables were needed because the three types summed to 100%. Sand and mud were the most strongly inversely correlated, so we omitted *Percent sand* to reduce multi-collinearity.

Effect size across levels of the categorical variables for both EN and EI models was determined by comparing marginal means. These means were output from generalized linear models (GLMs), which corrected for missing factor combinations and unbalanced designs to give equal weight to all levels of all other categorical variables. Marginal means for categorical variables in the EI model assumed values for the continuous variables were equal to their observed averages across all samples.

Table 1
Density of fishes captured by 3 m plumb staff beam trawl (PSBT) in the northeastern Chukchi Sea, by study area, 2009–2010. Catch is adjusted to count of fish per 1000 m^2, and averaged over hauls in the stratum. Species list is based on both types of benthic trawl collections combined. Dashes indicate zero catches.

Scientific and common names	**Study area**									**Over all hauls**	
	Klondike				Burger				Statoil	Mean	% Of
	Jul/Aug 2009	Sep/Oct 2009	Aug/Sep 2010	Mean	Jul/Aug 2009	Sep/Oct 2009	Aug/Sep 2010	Mean	Aug/Sep 2010	density	total fish density
Gadidae (Cods)											
Boreogadus saida Arctic cod	52.2	23.3	62.1	45.8	19.1	52.1	27.2	33.2	15.6	36.6	32.50%
Theragra chalcogramma Walleye pollock	–	–	–	–	–	0.2	–	< 0.1	–	< 0.1	< 0.1%
Cottidae (Sculpins)											
Artediellus scaber Hamecon	17.5	14.3	7	12.9	20.2	2.1	2.6	8	1.3	9.3	8.30%
Gymnocanthus tricuspis Arctic staghorn sculpin	6.4	19.4	8.4	11.4	0.9	0.1	0.6	0.5	–	5.3	4.70%
Hemilepidotus papilio Butterfly sculpin	0.1	–	–	< 0.1	–	–	–	–	–	< 0.1	< 0.1%
Icelus spatula Spatulate sculpin	–	1.4	–	0.5	2.5	0.2	3.3	2	–	1.1	0.9%
Myoxocephalus scorpius Shorthorn sculpin	5.6	41.6	14.3	20.5	1	4	2.1	2.4	0.6	10.2	9.1%
Trichocottus brashnikovi Hairhead sculpin	–	0.2	–	< 0.1	–	–	–	–	–	< 0.1	< 0.1%
Triglops pingelii Ribbed sculpin	0.3	1.4	0.5	0.7	–	0.4	–	0.1	–	0.4	0.3%
Hemitripteridae (Sailfin sculpins)											
Nautichthys pribilovius Eyeshade sculpin	0.1	0.9	–	0.4	–	–	–	–	0.4	0.2	0.2%
Agonidae (Poachers)											
Aspidophoroides monopterygius Alligatorfish	0.4	0.7	0.3	0.5	–	–	–	–	–	0.2	0.20%
Hypsagonus quadricornis Fourhorn poacher	–	–	0.2	< 0.1	–	–	–	–	–	< 0.1	< 0.1%
Ulcina olrikii Arctic alligatorfish	1.9	2.6	2.2	2.2	1.3	0.7	2.3	1.4	1.5	1.8	1.6%
Liparidae (Snailfishes)											
Liparis bathyarcticus Nebulous snailfish	0.8	1.3	–	0.7	0.3	0.6	–	0.3	–	0.4	0.4%
Liparis tunicatus Kelp snailfish	0.4	0.3	1.8	0.9	0.3	0.7	1.6	0.9	–	0.8	0.7%
Zoarcidae (Eelpouts)											
Gymnelus hemifasciatus Halfbarred pout	2	0.4	–	0.8	21.7	1.8	7.8	10.1	1.5	4.9	4.4%
Gymnelus viridis Fish doctor	0.3	1.1	–	0.5	4	1.1	1.5	2.1	0.4	1.2	1.0%
Lycodes mucosus Saddled eelpout	0.2	0.5	–	0.2	–	–	–	–	–	0.1	0.1%
Lycodes palearis Wattled eelpout	0.1	0.1	0.2	0.1	–	–	–	–	–	< 0.1	0.1%
Lycodes polaris Canadian eelpout	5.3	1.9	2.9	3.4	15.6	9.2	1.8	8.7	6	6	5.3%
Lycodes raridens Marbled eelpout	1.7	2.5	0.9	1.7	3.4	1.6	2	2.3	2.8	2.1	1.9%
Stichaeidae (Pricklebacks)											
Anisarchus medius Stout eelblenny	33.9	15.6	4.8	18.1	71.2	16.6	1.6	28.7	1.7	20.6	18.3%

Eumesogrammus praecisus	0.4	2.9	–	1.1	0.4	–	–	0.1	–	0.5	0.5%
Fourline snakeblenny											
Leptoclinus maculatus	–	–	–	–	0.2	–	–	< 0.1	–	< 0.1	< 0.1%
Daubed shanny											
Lumpenus fabricii	16.5	20.1	7.5	14.7	9.7	2.4	0.2	4	0.4	8.3	7.4%
Slender eelblenny											
Stichaeus punctatus	0.1	0.8	0.3	0.4	0.3	–	–	0.1	–	0.2	0.2%
Arctic shanny											
Ammodytidae (Sand lances)											
Ammodytes hexapterus	–	0.9	–	0.3	–	4.6	–	1.6	0.3	0.8	0.8%
Pacific sand lance											
Pleuronectidae (Righteye flounders)											
Hippoglossoides robustus	4.2	2.7	1.3	2.7	0.3	–	–	0.1	–	1.2	1.1%
Bering flounder											
Limanda proboscidea	–	0.2	–	< 0.1	–	–	–	–	–	< 0.1	< 0.1%
Longhead dab											
Total fish density—Mean ± St Dev	150.3 ± 148.7	156.9 ± 111.0	114.7 ± 116.3	140.6 ± 124.5	172.4 ± 137.0	98.4 ± 34.9	54.5 ± 92.1	106.8 ± 105.4	32.4 ± 26.6	112.5 ± 112.9	100.00%
Count of species	22	25	16	27	18	17	13	21	12	29	
Count of stations	13	13	13	39	12	13	13	38	11	88	

We used GLMs with discrete probability distributions to compute the likelihood of observing the counts of fish that were collected. These types of GLMs have become the standard approach for analyzing catch-per-unit-effort (CPUE) data (Power and Moser, 1999; Terceiro, 2003; Minami et al., 2007; Arab et al., 2008; Shono, 2008; Raborn et al., 2011). We considered both Poisson and negative binomial distributions to model these responses. Akaike's Information Criterion (AICc; Burnham and Anderson, 2002) was used to determine which of the two distribution types was most appropriate for the data being considered. It indicated that the negative binomial model was best for all response variables.

2.3. Spatial visualization of univariate fish community descriptors and environmental gradients

Each study area was visually characterized with contour maps of substrate variables, as well as the aforementioned univariate fish descriptor variables showing significant differences ($\alpha = 0.05$) across the three areas based on output from the EN model. Spatial contours of these variables were interpolated using ArcMap© 10 software and the spatial analyst extension (ESRI, Inc.). *Species richness, Density,* and *Bottom temperature* were interpolated by kriging data and allowing the ArcMap software to assign groups with natural breaks inherent in the data (Jenks Natural Breaks). Kriging generated an estimated surface from a scattered set of points with z-values; it does not necessarily present the full range of recorded data. Substrate data were interpolated with an inverse distance weighted model, which estimated cell values by averaging the values of sample data points in the neighborhood of each processing cell; break points were assigned manually at 10% intervals. Contours of *Species richness* and *Density* were calculated using only the PSBT from collections during 2009 and 2010. Temperature contours were created for each cruise separately; substrate contours were calculated as the average per station of all substrate samples examined for grain size, 2008–2010 (data from Blanchard et al., 2013a).

2.4. Statistical methods for a multivariate descriptor of the fish community

The multivariate response, *Assemblage structure*, was quantified for each sample by the relative abundances of all species. The relative abundance of a species is given by the CPUE of the species in the sample divided by the total CPUE of all species in the sample; thus, relative abundances for a given sample sum to one. *Assemblage structure* was analyzed using nonmetric multidimensional scaling (nMDS), which is a nonparametric ordination technique based on ranks and is insensitive to zeroes (Manzer and Shepard, 1962; Kruskal, 1964). All ordinations were performed with the statistical software PC-ORD (McCune and Mefford, 2006). Both axes exhibited p-values less than 0.01 based on comparing observed stress values with those derived from Monte Carlo runs of randomized data.

The nMDS ordination is an indirect gradient analysis whereby continuous variables must be correlated with the station axes *post hoc* and can be overlaid on the ordination biplot. The resulting biplot addresses Objective 1 by allowing visualization of the temporal and spatial variability in *Assemblage structure* across years and study areas, i.e., the distinctiveness of their respective fish communities. Towards addressing Objective 2, overlaying environmental variables with the station axis scores delineates how variability in assemblage structure correlated with these variables, which may indicate important environmental forcing of community dynamics. The biplot also can be used to determine if samples grouped by gear type (Objective 3).

Table 2
Density of fishes captured by 3 m beam trawl (3mBT) in the northeastern Chukchi Sea, by study area, 2010. Catch is adjusted to count of fish per 1000 m2, and averaged over hauls in the stratum. Species list is based on both types of benthic trawl collections combined. Dashes indicate zero catches.

	Study area			**Over all hauls**	
	Klondike Aug/Sep	Burger Aug/Sep	Statoil Aug/Sep	Mean density	% Of total fish
Scientific and common names	2010	2010	2010		density
Gadidae (Cods)					
B. saida Arctic cod	4.7	3.1	3.5	3.6	41.3%
T. chalcogramma Walleye pollock	–	–	–	–	–
Cottidae (Sculpins)					
A. scaber Hamecon	5.7	0.2	< 0.1	1.3	14.7%
G. tricuspis Arctic staghorn sculpin	2.7	< 0.1	–	0.6	6.5%
H. papilio Butterfly sculpin	–	–	–	–	–
I. spatula Spatulate sculpin	–	< 0.1	< 0.1	< 0.1	0.6%
M. scorpius Shorthorn sculpin	1.6	< 0.1	< 0.1	0.4	4.3%
T. brashnikovi Hairhead sculpin	< 0.1	–	–	< 0.1	0.1%
T. pingelii Ribbed sculpin	0.3	< 0.1	< 0.1	< 0.1	1.0%
Hemitripteridae (Sailfin sculpins)					
N. pribilovius Eyeshade sculpin	1.5	–	–	0.3	3.4%
Agonidae (Poachers)					
A. monopterygius Alligatorfish	–	–	–	–	–
H. quadricornis Fourhorn poacher	0.1	–	–	< 0.1	0.3%
U. olrikii Arctic alligatorfish	0.8	0.2	0.1	0.3	3.1%
Liparidae (Snailfishes)					
L. bathyarcticus Nebulous snailfish	–	–	< 0.1	< 0.1	0.1%
L. tunicatus Kelp snailfish	0.4	< 0.1	< 0.1	0.1	1.7%
Zoarcidae (Eelpouts)					
G. hemifasciatus Halfbarred pout	0.1	0.1	–	< 0.1	0.9%
G. viridis Fish doctor	< 0.1	< 0.1	–	< 0.1	0.6%
L. mucosus Saddled eelpout	–	–	–	–	–
L. palearis Wattled eelpout	–	–	–	–	–
L. polaris Canadian eelpout	0.3	1.0	0.4	0.6	7.1%
L. raridens Marbled eelpout	0.4	0.3	0.1	0.2	2.6%
Stichaeidae (Pricklebacks)					
A. medius Stout eelblenny	0.5	0.9	0.4	0.6	7.0%
E. praecisus Fourline snakeblenny	0.4	< 0.1	–	< 0.1	1.0%
L. maculatus Daubed shanny	–	–	–	–	–
L. fabricii Slender eelblenny	0.6	0.2	< 0.1	0.2	2.6%
S. punctatus Arctic shanny	0.2	–	–	< 0.1	0.5%
Ammodytidae (Sand lances)					
A. hexapterus Pacific sand lance	< 0.1	–	–	< 0.1	0.1%
Pleuronectidae (Righteye flounders)					
H. robustus Bering flounder	< 0.1	< 0.1	< 0.1	< 0.1	0.5%
L. proboscidea Longhead dab	–	–	–	–	–
Total fish density—Mean ± St Dev	20.5 ± 13.8	6.3 ± 6.0	4.9 ± 5.9	8.7 ± 9.8	100.0%
Count of species	20	16	13	23	
Count of stations	6	13	11	30	

Sampling across factor combinations was unbalanced and missing altogether for some combinations; the 3mBT was used only in 2010, and Statoil was sampled only in 2010. The nMDS ordination cannot correct for missing factor combinations or unbalanced sampling; therefore, any differences in how samples from a given categorical variable group together in the ordination biplot may be confounded by influences from other variables. For GLMs the multivariate *Assemblage structure* was reduced to two univariate descriptors, *axis* 1 and *axis* 2, which are the coordinates that position samples in the ordination biplot. Similar approaches have been used successfully to assess assemblage structures of other systems (Matthews, 1987; Gelwick, 1990; Raborn et al., 2001). The GLMs correct for imbalances and fill in missing data to isolate the effect of each categorical variable on the "average" *Assemblage structure*. We assumed axis 1 and axis 2 were normally distributed when parameterizing their GLMs.

3. Results

3.1. Effort and catch summaries

In total, 37 distinct stations were trawled 2–4 times during this study (Fig. 1). These stations were systematically spaced in each of the study areas: 13 in Klondike, 13 in Burger, and 11 in Statoil. All effort totaled 161,316 m^2 of bottom sampled with the two demersal trawl types. The majority of this total area was sampled with the 3mBT in 2010 because it was deployed for ~15–30 min during each tow as opposed to the ~3–5 min tow durations with the PSBT.

A total of 29 species were represented in the combined demersal trawl collections (Tables 1 and 2). The 10 most abundant species in the PSBT and 3mBT collections made up 93% and 90% of the total catch, respectively. In order of overall abundance, those species were Arctic cod, stout eelblenny, shorthorn sculpin (*Myoxocephalus scorpius*), hamecon (*Artediellus scaber*), slender eelblenny (*Lumpenus fabricii*), Canadian eelpout, Arctic staghorn sculpin, halfbarred pout (*Gymnelus hemifasciatus*), marbled eelpout (*Lycodes raridens*), and Arctic alligatorfish (*Ulcina olrikii*). Of the five most abundant species collected for each trawl type, three species were common to both lists: Arctic cod, hamecon, and stout eelblenny. Eight species of sculpins were captured by each gear type, which is more than for any other fish family occurring in the study area (Tables 1 and 2). Arctic cod was the dominant taxon caught by both trawls, composing 33% of the PSBT and 41% of the 3mBT collections.

Overall, both the total density of fishes caught and the number of species taken in both types of demersal trawls were highest in the more southerly Klondike study area and were much lower in the more northerly Burger and Statoil study areas. In the 2009 PSBT collections for Klondike (Table 1), total fish densities were similar in July/August and September/October 2009, and approximately 25% lower in August/September 2010 (151, 157 and 115 fish per 1000 m^2, respectively). Likewise, the Klondike collections in July/August and September/October 2009 caught more species than were caught in August/September 2010 (22, 25, and 16 species, respectively). In the PSBT collections from Burger, total fish densities declined from a peak in July/August 2009 by approximately 40% in September/October 2009, and by 70% in August/September 2010 (173, 98, and 55 fish per 1000 m^2, respectively). Similar to Klondike, higher numbers of species were caught in Burger during July/August and September/October 2009 than in August/September 2010 (18, 17, and 13 species, respectively). Though the density and number of species in the 2010 PSBT collections were low in Klondike and Burger, they were even lower in Statoil with only 32 fish per 1000 m^2 and 12 species captured (Table 1). In August/September 2010 the 3mBT total fish density was 3–4 times higher in Klondike than in Burger or Statoil (21, 6, and 5 fish per 1000 m^2, respectively). The number of species captured in Klondike was highest, with fewer species caught in Burger and fewer still caught in Statoil (20, 16, and 13 species, respectively).

The demersal trawl collections were dominated numerically by small fishes. Of the 27 species captured by the PSBT, the maximum sizes of 10 species were < 100 mm, of 11 species were 100–149 mm,

Table 3
Predicted responses of categorical variables from the environmentally naive (EN) and environmentally informed (EI) generalized linear models of demersal fishes in the northeastern Chukchi Sea. Predicted marginal mean values (the means that are estimated while holding all other variables constant) are reported for each response variable as density of fish, i.e., count per 1000 m^2. Models are based on 2009–2010 collections with both bottom trawl gears.

Predicted marginal mean	**Study area**				**Year**			**Gear**		
	Klondike	Burger	Statoil	*p*	2009	2010	*p*	PSBT	3mBT	*p*
Environmentally naive model										
Species richness	4.97	5.09	3.383	0.032	4.46	4.35	0.836	14.20	1.37	< 0.001
Total fish density	50.36	30.13	18.59	< 0.001	42.36	21.88	0.001	81.38	11.39	< 0.001
Arctic cod	15.23	10.82	8.61	0.219	11.34	11.13	0.945	32.26	3.91	< 0.001
Arctic staghorn sculpin	5.33	0.17	< 0.01	< 0.001	0.01	< 0.01	0.632	0.01	< 0.01	0.032
Canadian eelpout	1.12	2.74	2.10	0.043	2.63	1.32	0.094	5.00	0.69	< 0.001
Stout eelblenny	4.33	5.38	2.56	0.294	12.28	1.24	< 0.001	8.43	1.81	< 0.001
Bering flounder	0.74	0.03	0.24	0.001	0.31	0.11	0.041	0.48	0.07	0.012
Assemblage structure										
nMDS axis 1	−0.02	0.082	−0.052	0.593	0.202	−0.193	0.003	0.023	−0.014	0.798
nMDS axis 2	0.35	−0.171	−0.491	< 0.001	−0.033	−0.173	0.245	−0.039	−0.167	0.327
Environmentally informed model										
Species richness	4.79	4.48	4.30	0.926	4.67	4.37	0.76	14.86	1.37	0.001
Total fish density	38.07	31.12	19.00	0.306	43.70	18.24	0.035	82.92	9.61	< 0.001
Arctic cod	12.88	11.33	6.42	0.460	16.25	5.89	0.055	27.17	3.52	< 0.001
Arctic staghorn sculpin	0.30	0.34	< 0.01	0.994	0.01	< 0.01	0.627	0.01	< 0.01	0.002
Canadian eelpout	2.47	1.56	0.20	0.024	0.84	1.02	0.828	2.26	0.38	< 0.001
Stout eelblenny	7.57	3.95	0.50	0.013	6.91	0.88	0.016	4.79	1.27	0.002
Bering flounder	0.29	0.07	0.06	0.425	0.09	0.13	0.715	0.21	0.05	0.052
Assemblage structure										
nMDS axis 1	0.315	−0.073	−0.485	0.057	−0.055	−0.106	0.858	−0.090	−0.072	0.898
nMDS axis 2	−0.053	−0.033	−0.009	0.988	0.020	−0.084	0.672	0.061	−0.125	0.128

of 3 species were 150–199 mm, and of only 3 fish species were >200 mm. The largest fish taken in the PSBT collection was a 225 mm TL marbled eelpout (*L. raridens*) taken in Klondike during August/September 2010. The maximum sizes of the 23 species taken in the 3mBT were similar to those of the PSBT: 10 species were <100 mm, 9 species were 100–149 mm, 1 species was 150–199 mm, and 3 species were >200 mm. A 250 mm TL shorthorn sculpin collected in Klondike in August/September 2010 was the largest fish taken in the 3mBT. Captured fishes in mid-shelf area of the Chukchi Sea were almost all <150 mm TL.

3.2. Objective 1: Comparison of fish community descriptors across study areas and years

The EN model detected significant differences ($p<0.05$) among study areas for *Species richness*, *Total fish density*, and the *densities* of Arctic staghorn sculpin, Canadian eelpout, and Bering flounder (Table 3). These estimated fish densities were greatest in the more southerly Klondike study area, with the exception of Canadian eelpout which was higher in Burger. *Total fish density*, stout eelblenny *density*, and Bering flounder *density* declined significantly from 2009 to 2010.

The contour maps show the number of species and density of fishes to be the highest in Klondike and lowest in Statoil. *Species richness* was concentrated in the center east of Klondike (Fig. 2). For both gears, there were 28 fish species captured in Klondike, 24 species in Burger, and 17 species in Statoil (Tables 1 and 2). Up to 21 species were captured at one station in Klondike, while as few as three were caught in Statoil. *Total fish density* was higher and more homogenously high throughout Klondike and increased somewhat at the southern and western edges, but was concentrated towards the center of the Burger study area (Fig. 3). Arctic cod was the most abundant and evenly distributed species, though the density was low in Statoil (Fig. 4). The southeast corner of Klondike had high concentrations of Arctic staghorn sculpin, and very few were captured in the other two study areas (Fig. 5). Canadian eelpout was concentrated in the northwest corner of the Burger study area, overlapping into the southeast corner of Statoil (Fig. 6). Canadian eelpout was almost absent from the southeast part of Klondike. Stout eelblenny had the highest densities in Burger and the lowest in the northwest corner of the Statoil study area (Fig. 7). Bering flounder was found throughout Klondike, especially concentrated in north central, and was extremely low in Burger and Statoil (Fig. 8).

Patterns were seen in fish densities between years and among study areas (Fig. 9). Between-year variability could be seen along the x-axis (axis 1) of the nMDS ordination biplot, with more 2009 collections on the right and 2010 collections on the left. Between

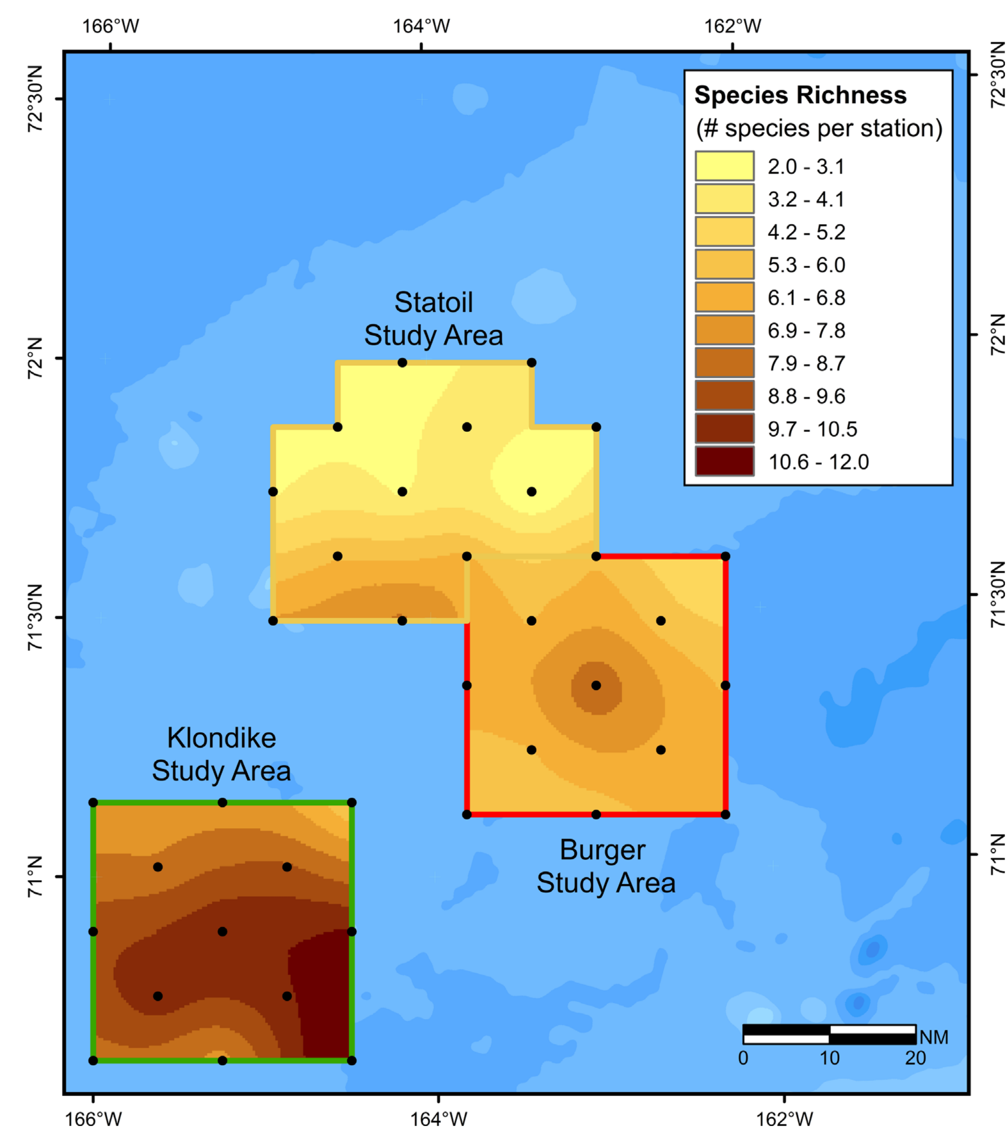

Fig. 2. Species richness among and within each of the Klondike, Burger and Statoil study areas based on plumb staff beam trawl collections, northeastern Chukchi Sea 2009–2010.

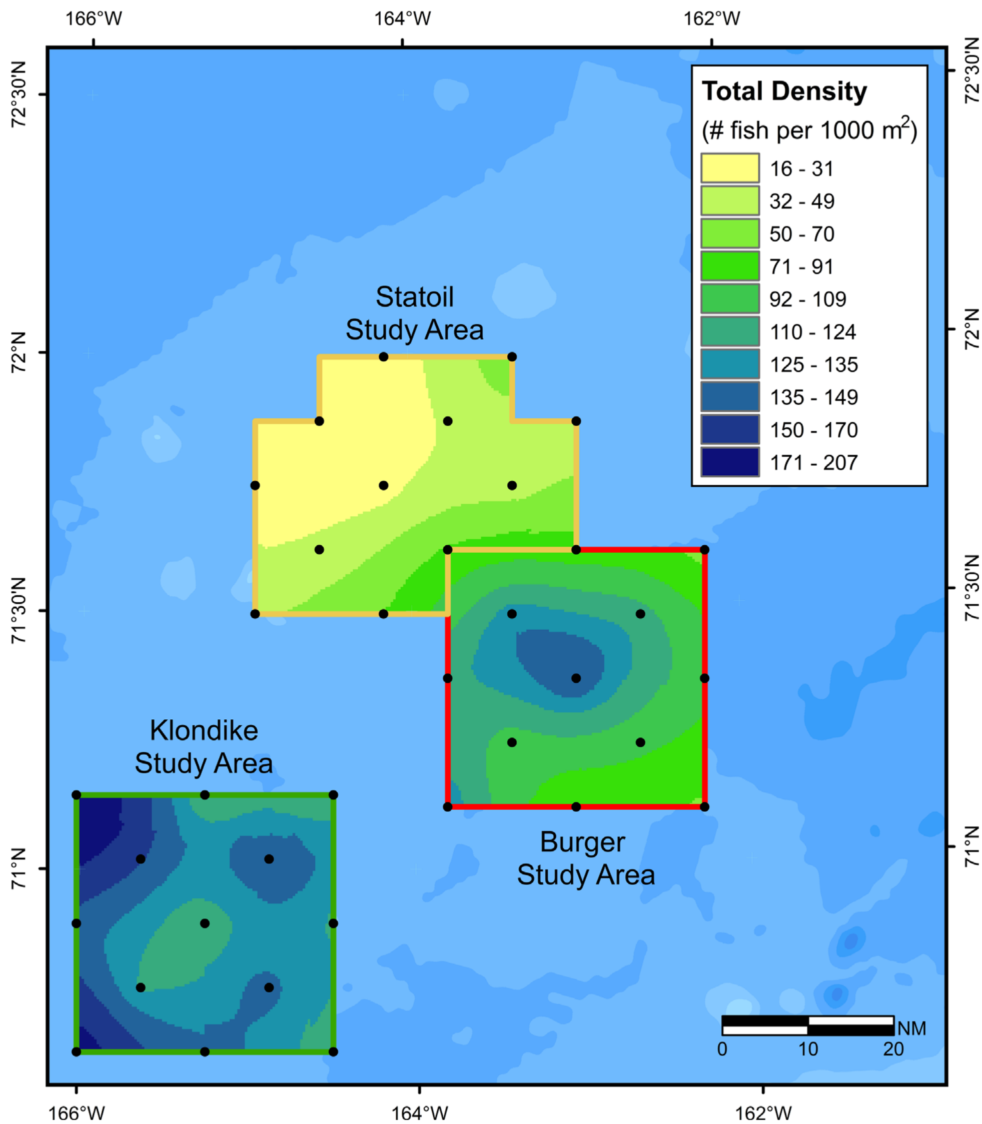

Fig. 3. Total relative density of fish among and within each of the Klondike, Burger and Statoil study areas based on plumb staff beam trawl collections, northeastern Chukchi Sea 2009–2010.

study areas variability of stations was apparent along the *y*-axis (axis 2), especially between Klondike and Burger on the right side of the plot and Statoil station grouping in the upper left quadrant. Klondike stations were widely distributed in nMDS space and dominated the top half of the plot (Fig. 9). The stations of Statoil grouped much more tightly together than those of the other study areas; more stations overlapped those of Burger than of Klondike.

Twenty-nine demersal species showed patterns affiliated with study areas within families in the nMDS ordination (Fig. 9). The gadids had different distributions; Arctic cod, but not walleye pollock (*Theragra chalcogramma*), had greater relative representation in the fish communities of Burger and Statoil. The seven sculpin species were associated more with Klondike. All three poachers were connected to Klondike stations. The eelpouts were associated with all three study areas. The pricklebacks grouped with most of the sculpins and primarily with Klondike and secondarily with Burger. The two flatfishes were not aggregated with each other; longhead dab seemed to be related to Klondike and Statoil areas, whereas Bering flounder was located in the center of the nMDS plot in a predominantly Klondike area. No flatfish species were distributed in the Burger–Statoil quadrant.

3.3. *Objective 2: Relating changes in the fish descriptor variables to environmental gradients*

Physical environmental characteristics, as determined by other researchers of the CSESP, were found to differ among study areas. Bottom temperature (Weingartner et al., 2013) varied more and was higher overall in the more southerly Klondike study area (Fig. 10), though these differences both within Klondike and across all study areas were less in 2009. In 2010, the differences in bottom temperatures between study areas ranged from 1 °C to 5 °C in Klondike and from −1.5 °C to 1 °C in Burger and Statoil. *Salinity* was homogenous and varied only 1–2 throughout the entire study. Sediments (Blanchard et al., 2013a) were less coarse at the northerly Burger and Statoil study areas. *Percent gravel* was greater and more variable in Klondike (0–60%), but reduced and more homogenous in Burger (0–15%) and Statoil (0–20%) (Fig. 11). Conversely, *Percent mud* was reduced in Klondike (10–65%) and as high as 92% in Burger; mud percentages in Statoil were intermediate, though more aligned with those of Burger (Fig. 11). *Depth* was mostly uniform and similar across study areas (Fig. 1).

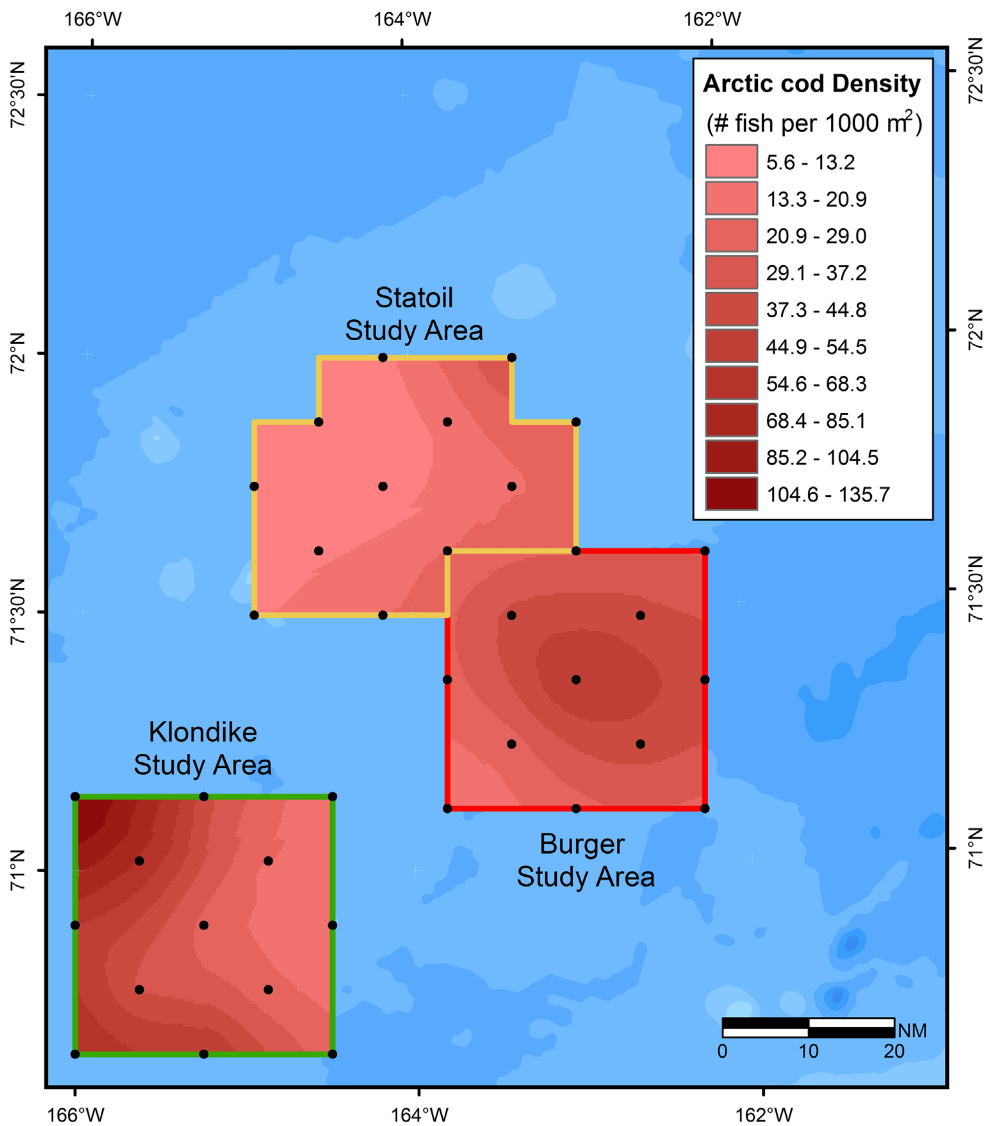

Fig. 4. Relative density of Arctic cod within each of the Klondike, Burger and Statoil study areas based on plumb staff beam trawl collections, northeastern Chukchi Sea 2009–2010.

The study areas oriented with the environmental variables. The Klondike axis scores tended to correlate more positively with *Percent gravel* and *Salinity* and more negatively with *North, Percent mud* and *East* (Fig. 9). The directions of these correlations were reversed for Burger and Statoil; however, two stations in the southern part of the Burger study area were not closely associated with Burger or with Klondike. Statoil was related to *Distance offshore.*

The EI model results did not directly mimic those of the EN model. There were fewer significant differences among study areas detected with the EI model (Table 3), which suggested that the environmental gradients underlying the differences among study areas detected with the EN model were captured by the variables included in the EI model. While stout eelblenny *density* still differed, Canadian eelpout *density* switched from being non-significant in the EN model to significant in the EI model. Individual environmental gradients did not account for differences across years as the decline in *Total fish density* and stout eelblenny *density* from 2009 to 2010 remained significant. Furthermore, the 2010 decline in Arctic cod *density* became significant with the EI model.

Output from the EI model showed that environmental variables did not affect all fish equally (Table 4). *Species richness* was positively correlated to *Salinity* and *Temperature.* Arctic cod was the only species related to *Temperature*, and Canadian eelpout was the only species correlated with *Salinity. Total fish density* and Arctic staghorn sculpin *density* were negatively correlated with *Depth.* Arctic cod *density* was positively related to *Distance* offshore. Arctic cod and Arctic staghorn sculpin were negatively associated with more northern *Latitude*, while *Total fish density* and Arctic cod *density* were positively correlated with *Longitude. Species richness, Total fish density* and Arctic cod were positively correlated with *Percent mud* and with *Percent gravel.* Stout eelblenny and Bering flounder were negatively related to *Percent gravel.*

The families of fishes represented in the three study areas grouped to differing degrees with the continuous environmental variables in the nMDS ordination plot (Fig. 9). Arctic cod oriented with *Distance offshore,* while the only other gadid, walleye pollock, was caught in low numbers yet seemed to be aligned with *Percent gravel.* Most of the sculpins lined up with *Percent gravel* and *Salinity*, but butterfly sculpin differed by being associated with *Distance offshore*. The poachers were centrally located and not strongly aligned with any environmental variable. The eelpout family did not follow a uniform association pattern: one with

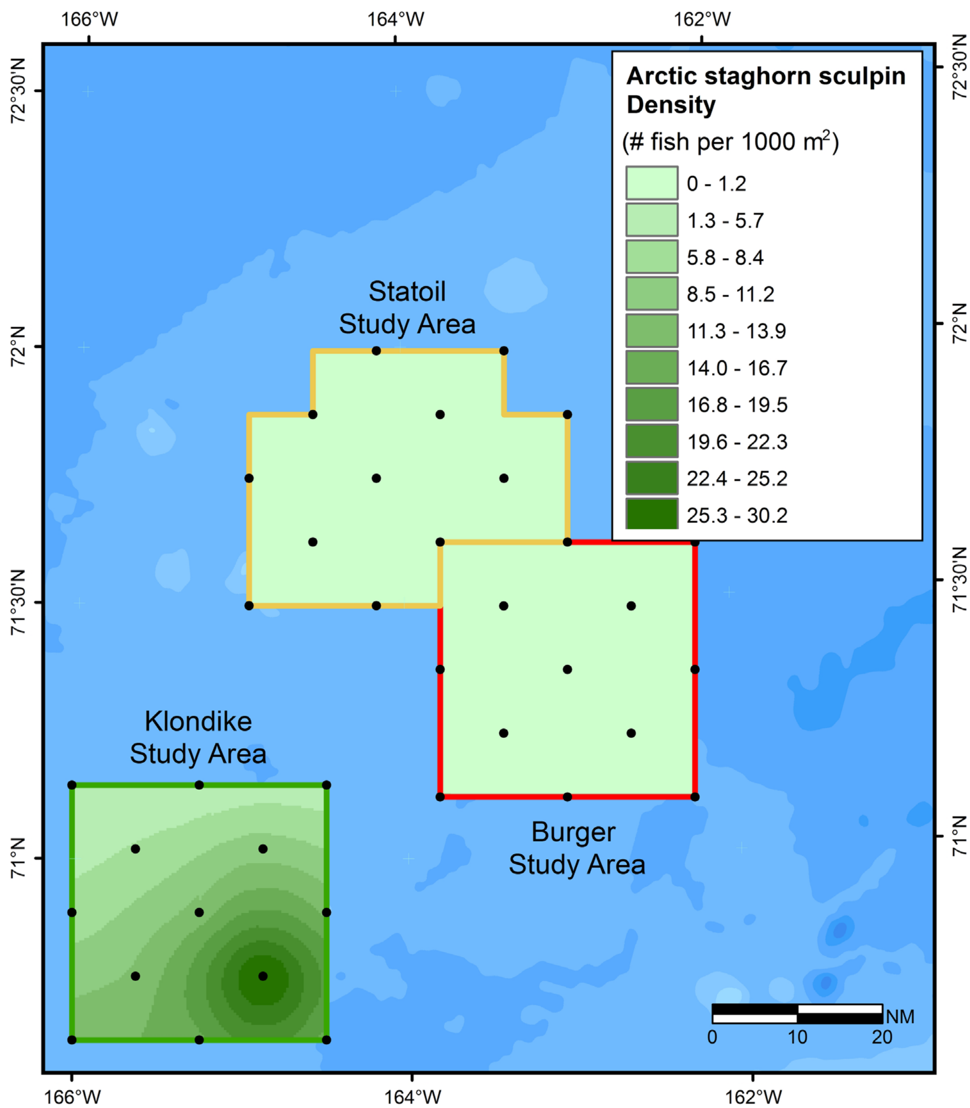

Fig. 5. Relative density of Arctic staghorn sculpin within each of the Klondike, Burger and Statoil study areas based on plumb staff beam trawl collections, northeastern Chukchi Sea 2009–2010.

none, two with *Temperature*, and two with depth. Most pricklebacks were positioned between *Percent gravel* and *Salinity*, although stout eelblenny was somewhat different in that it was closer to a snailfish between *Depth* and *Salinity*. Bering flounder was weakly aligned between *Depth* and *Salinity*, while longhead dab was positioned on the *Temperature* vector.

The EI model indicated that *Assemblage structure* was not related to the environmental variables. Neither of the Assemblage structure variables, axis 1 or axis 2, differed among study sites or years (Table 3). However, *Percent gravel* was significant for axis 1, *Study area* in the EN model and *Depth* was significant for axis 2, *Year* in the EN model (Table 4).

3.4. Objective 3: Gear effects

When both nets were used at the same stations in 2010, it was apparent that the PSBT (Table 1) and the 3mBT (Table 2) did not sample equally. In Klondike, Burger, and Statoil the mean CPUE of fish captured was 4 to 8 times greater with the PSBT than with the 3mBT. All fish *density* variables were statistically greater for the PSBT than the 3mBT in both the EN and EI models (Table 3). The magnitude of these differences was greater for *Species richness*, *Total fish density*, and Arctic cod. The two gear types did not seem to ordinate into distinct groups, which indicates they provided similar indices of *Assemblage structure*. Neither the EN model nor EI model detected significant differences in axis 1 and axis 2 between gear types (Table 3). Though fewer fishes were caught with the 3mBT, in each of the study areas that net captured more species than the PSBT did; approximately 25% more species were caught in Klondike and Burger and 8% more species in Statoil (Tables 1 and 2). However, diversity was greater with the PSBT, which captured 29 species compared to the 22 species taken with the 3mBT.

4. Discussion

The three closely-spaced study areas in the northeast Chukchi Sea yielded 29 species from nine families, which is a large number in comparison to 52 species from 13 families collected in the eastern Chukchi Sea in 1990–1991 and 2004–2008 and 80 species of fish in 19 families recorded across a widespread area of the both the eastern and western Chukchi Sea_1959 to 2008 (Norcross et al., 2013). The relatively low species richness for Chukchi Sea demersal fish communities over time is consistent with the latitudinal diversity gradient phenomenon (Hillebrand, 2004). This phenomenon may be

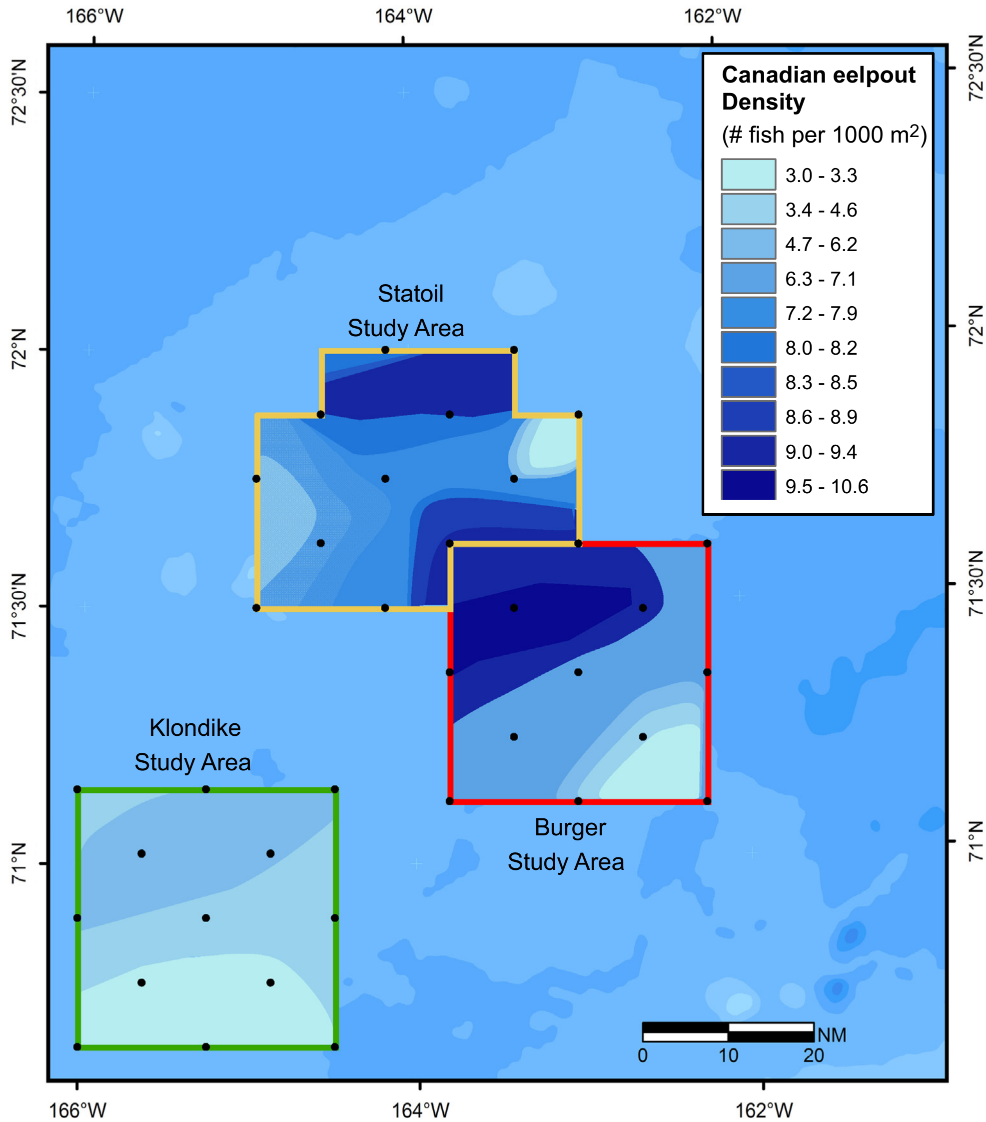

Fig. 6. Relative density of Canadian eelpout within each of the northeastern Chukchi Sea Klondike, Burger and Statoil study areas based on plumb staff beam trawl collections, 2009–2010.

due to multiple factors and is still open for debate in theoretical ecology (see Willig et al., 2003). One prevailing hypotheses involves evolutionary time (Rohde, 1992), i.e., arctic fishes are evolutionarily young and have not yet expanded into all niches (Eastman, 1997). Though a recent analysis of biodiversity determined that there are 242 species of marine fishes across the entire arctic region (Mecklenburg et al., 2011), it is apparent that the more limited the area sampled, such as the small-scale study areas presented here, the fewer species are encountered.

Similar to what was found using a larger otter trawl (Barber et al., 1997), the top 10 species collected by both the PSBT and 3mBT composed ~92% of the total catch. Arctic cod numerically dominated samples collected with both gear types across all study areas and both years. However, the dominant demersal fish species captured over the three cruises of this study differed somewhat from previous studies. Hamecon, half-barred pout and marbled eelpout were also among the top 10 most abundant species captured in this study, but not in 1990–2008 (Barber et al., 1997; Norcross et al., 2013). Conversely, saffron cod (*Eleginus gracilis*) and Bering flounder (*H. robustus*) were among the most abundant fishes in 1990–2008, but neither was ranked in the top 10 species in this study. Though saffron cod may be found to depths of 200 m, it is usually found in shallower waters (Mecklenburg and Mecklenburg, 2011) and nearer shore (Cohen et al., 1990; Mecklenburg et al., 2007) than the offshore location of the three study locations. Bering flounder abundance increases in the southern part of the Chukchi Sea (Pruter and Alverson, 1962; Smith et al., 1997a, 1997b), which is affirmed by its presence only in Klondike and not in the northern study sites.

Indicator species, each from a different family, were chosen to represent numerical dominance, geographic distribution, and trophic level at which they feed. Arctic cod and Arctic staghorn sculpin, Gadidae and Cottidae, respectively, have circumpolar distributions (Mecklenburg et al., 2011) and are recommended as indicator monitoring species for pelagic and demersal fish communities of the Chukchi Sea (Mecklenburg et al., 2008). Though considered cryopelagic, Arctic cod is bottom-associated over Arctic continental shelves (Bluhm and Gradinger, 2008). As one of the most abundant fishes in the Chukchi Sea (Lowry and Frost, 1981; Barber et al., 1997), it is an important prey for many bird and marine mammal species (Frost and Lowry, 1980; Piatt et al., 1990). Arctic staghorn sculpin is widespread throughout the Chukchi Sea (Andriashev, 1954; Frost and Lowry, 1980). Collectively, sculpins represent the second-most-abundant family of fishes in the

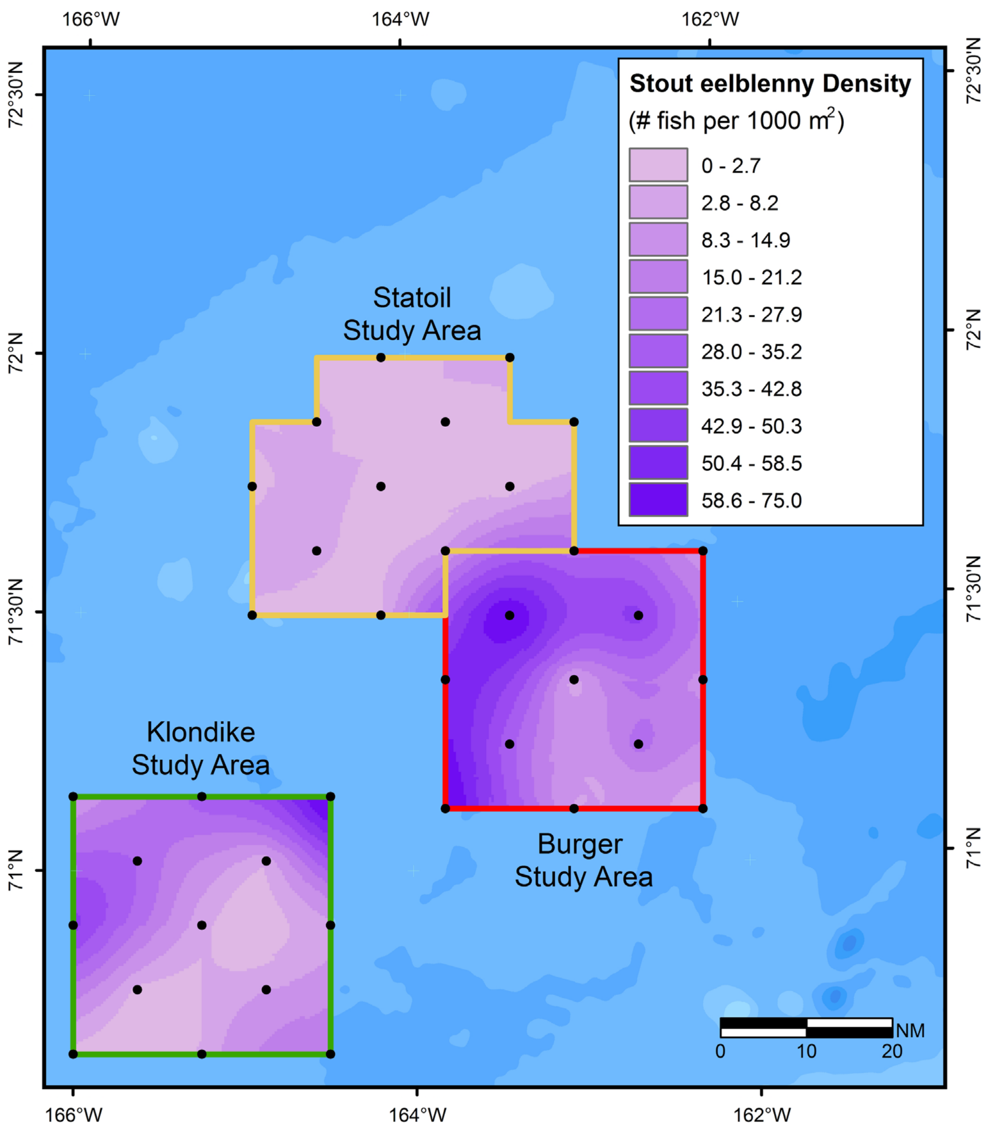

Fig. 7. Relative density of stout eelblenny within each of the Klondike, Burger and Statoil study areas based on plumb staff beam trawl collections, northeastern Chukchi Sea 2009–2010.

Chukchi Sea in terms of total number of fish caught (Barber et al., 1997; Norcross et al., 2013). In some areas of the Chukchi Sea, sculpin is the most numerous family, and Arctic staghorn sculpin is the most abundant species (Mecklenburg et al., 2007). Canadian eelpout and stout eelblenny represent two families, Zoarcidae and Stichaeidae, respectively, and may be numerous. Finally, Bering flounder is generally not as abundant as the other four indicator species (Barber et al., 1994; Mecklenburg et al., 2007), but it is the most abundant flatfish in the Chukchi Sea. Bering flounder is the most piscivorous of the five, and represents a higher trophic level (Mecklenburg and Mecklenburg, 2011). While the five species overlap in their diets, their collective trophic breadth captures that of the entire demersal fish community (Edenfield et al., 2011). These species were not similarly or uniformly distributed across the three study areas.

The species richness, density, and assemblage structure of the demersal fish community differed among the three study areas. The more southerly Klondike study area had greater species richness and densities, which fits with historical analysis. The Chukchi Sea north of Cape Lisburne to Point Lay had greater species richness than areas to the north and east in all past analysis: 1973–1983, 1989–1992 and 2004–2008 (Norcross et al., 2013). Likewise, the assemblage structure differed among study areas, and fish assemblages separated roughly corresponding to these areas, i.e., at about Point Lay, during_1990–1991 (Norcross et al., 2013). The broader ordination of the Klondike samples suggests greater variation in assemblage structure within Klondike, which fits with the increased species richness in that area. The difference in infauna communities by study area was similar to that of demersal fish communities, in that Klondike is more separate, whereas Burger and Statoil have considerable overlap (Blanchard et al., 2013a).

When environmental variables were used in the EI model, study area no longer affected richness and assemblage structure. Richness and density could be explained by the environmental variables that defined the overall study area. Klondike and Burger both appear to be influenced primarily by Bering Sea Water, albeit differently at times, as the water may go northward and clockwise around Hanna Shoal before flowing southward to approach the Burger study area from the east (Weingartner et al., 2013).Perhaps more importantly, during the study period, colder winter bottom water persisted longer over Burger. Klondike was typically warmer (Weingartner et al., 2013), shallower, and characterized by more gravel and rocky substrates with less mud

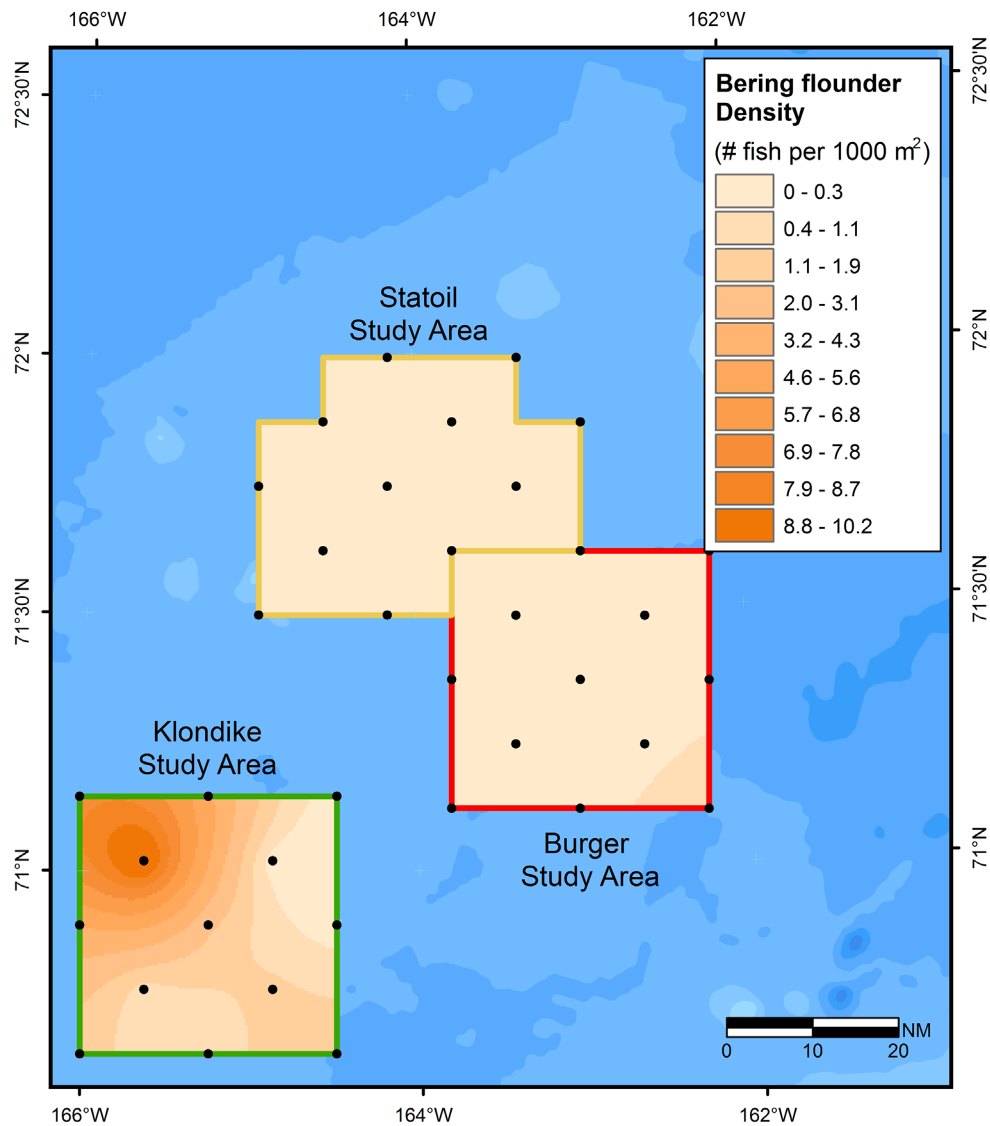

Fig. 8. Relative density of Bering flounder within each of the Klondike, Burger and Statoil study areas based on plumb staff beam trawl collections, northeastern Chukchi Sea 2009–2010.

(Blanchard et al., 2013a). The variables salinity, temperature, percent gravel and percent mud directly reflect these characteristics, thus the EI model results are verified by the field observations of related studies. Currents and sediment characteristics suggest that Klondike is erosional compared to the more depositional environments in the Burger and Statoil study areas. Although the density of infauna, i.e., fish food, in Klondike is 2–3 times less than in Burger or Statoil (Blanchard et al., 2013a), there was an inverse relationship with the density of demersal fishes. Likewise, Klondike was characterized by lower densities of megafaunal invertebrates, especially brittle stars, which were extremely abundant in Burger (Blanchard et al., 2013b). The inverse fish to invertebrate relationship could be enhanced by increased predation on benthic invertebrate communities by higher abundance of demersal fishes in erosional environments.

Even with environmental variables added to the EI model, total fish and stout eelblenny densities still differed between years. This suggests that redistribution along annually changing gradients was not the cause of these temporal differences; rather, annual fluctuation in fish density was independent of these gradients. When zooplankton abundance was highest in 2010 (Questel et al., 2013) density of fish was the lowest. Conversely, when fish density was higher in 2009 zooplankton abundance was lower. Except for Arctic cod, the demersal fish in this study were not eating very much zooplankton as shown by analysis of stomach contents (Edenfield et al., 2011). Overly abundant zooplankton that are not consumed in the pelagic realm would fall to sea floor and become food for the benthic food sources that then are consumed by most of these demersal fish species. Either the zooplankton were consumed and did not contribute to the benthos, or there is a lag time before the effect of abundant food was observed on fish density.

The fishes collected were uniformly small, with most <150 mm. The small size of fishes caught in our samples was likely representative of the population as a whole. It could be argued that the small sizes we observed were an artifact of the small demersal trawls used for this study. However, hauls made by larger trawls with larger mesh, albeit at 1–2 times the speed (Barber et al., 1997; Logerwell et al., 2010), confirm that marine fish communities on the shelves of the Chukchi Sea and western Beaufort Sea are comprised mainly of small fishes.

The type of gear used to monitor fish populations in future studies is a particularly important consideration, and must be

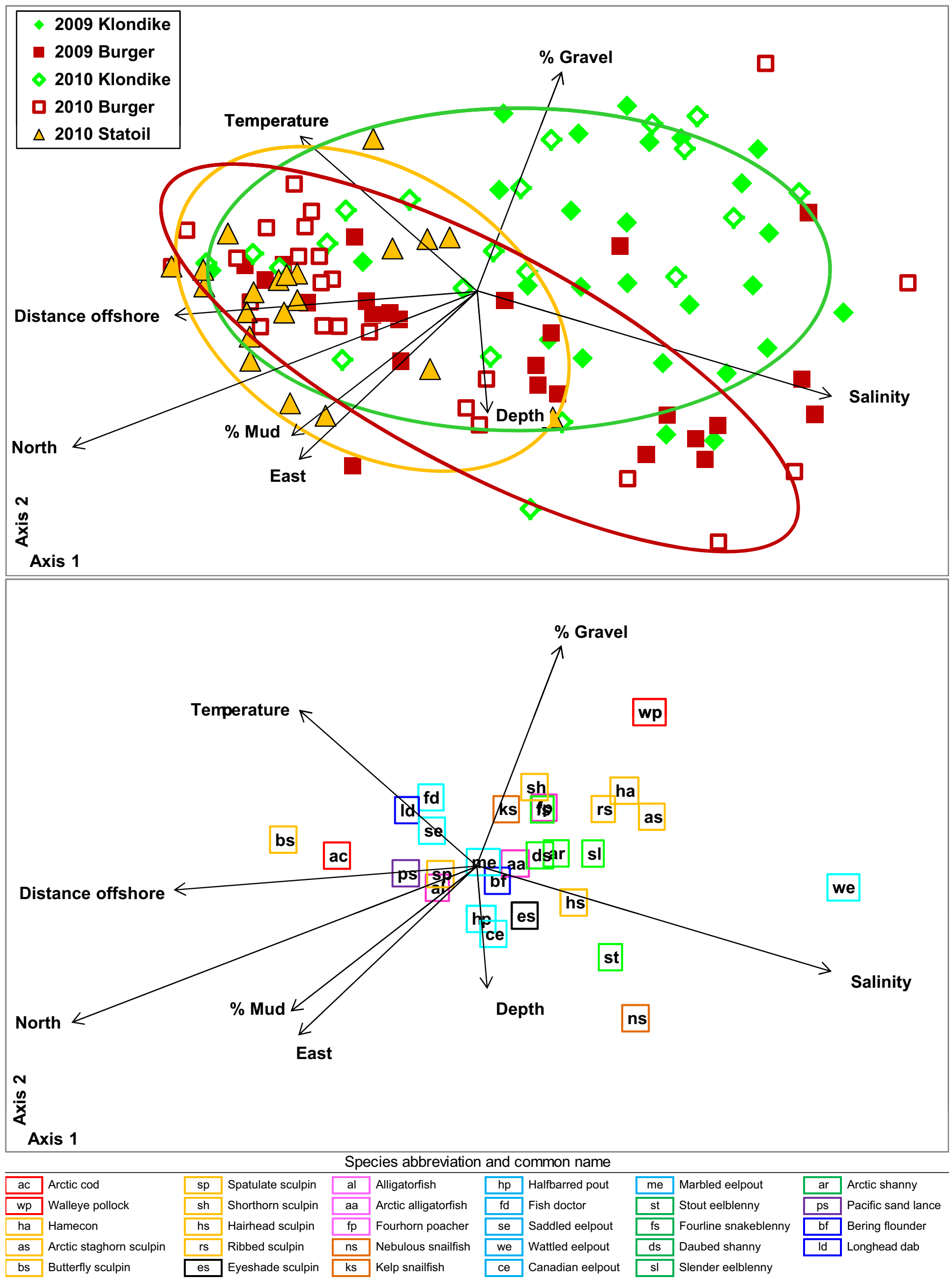

Fig. 9. Nonmetric multidimensional scaling (nMDS) ordination. Magnitude and direction of continuous variable correlations indicated by solid black arrows. Top: stations sampled in three study areas in 2009 and 2010 by plumb staff beam trawl and 3 m beam trawl. Ellipses illustrate station groupings for each study area. Bottom: individual demersal fish species' relative densities. Colors indicate fish families.

taken into account when evaluating differences in fish densities and community structure. For example, the PSBT captured eight times more fish than did the 3mBT although both nets were the same size and towed at the same speed. The difference in catches could have been because the PSBT disturbed the substrate more causing the catchability of demersal species to increase. The 3mBT does not dredge into the bottom, but rather skates above the substrate while being towed, possibly allowing fish to pass under the net rather than being captured. Another probable explanation is that the 4 mm mesh of the PSBT liner, which was a third the size of the 3mBT liner, not only allowed very small fishes to be retained, but also retained mud further preventing escape of fishes through the net. Analysis of historical data (Norcross et al., 2013) was confounded by use of many types of trawl gear, but compared with nets having larger mesh and towed at faster speeds such as used by Barber et al. (1997), the PSBT catch of fish was much greater (Norcross et al., 2013).

The demersal fish community in the arctic is highly dependent upon the boundaries of the individual water masses (Barber et al., 1994; Norcross et al., 2011a, 2011b). Water flux into the northeastern Chukchi Sea transports fishes from the Bering Sea (Wyllie-Echeverria et al., 1997) impacting assemblage structure within the study area. If the northern Bering Sea fish community changes in response to changing environmental conditions (Grebmeier et al., 2006), effects should be seen in the Chukchi Sea. Future studies and development planning may use these results to predict areas of ecological shifts in response to environmental changes.

Areas of increased richness and/or densities suggest a lack of ecological homogeneity across a relatively small geographic area within the Chukchi Sea. Our results indicate extreme caution

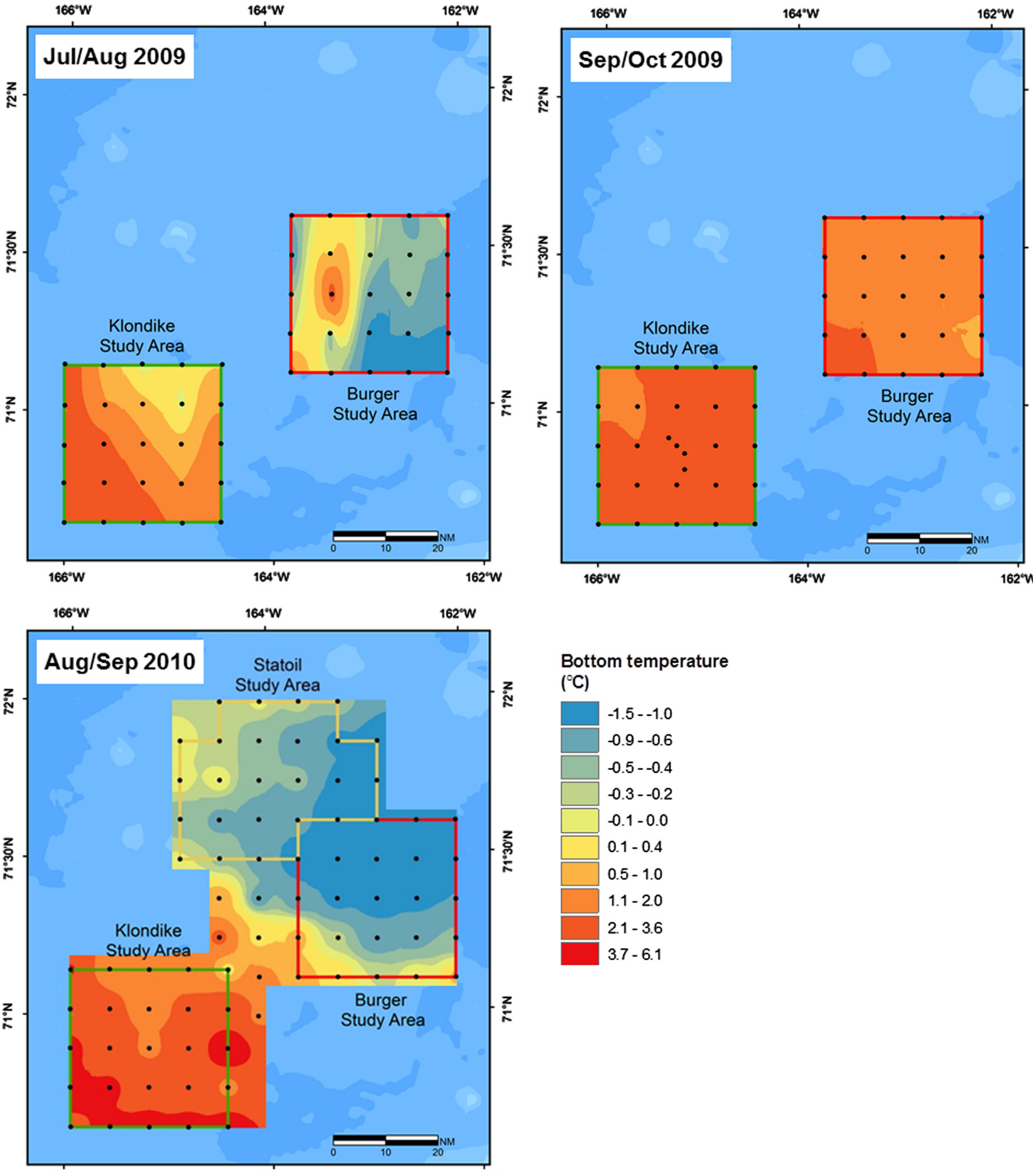

Fig. 10. Bottom water temperature (°C) by study area and cruise, 2009–2010 (data from Weingartner et al., 2013).

should be used when applying specific information from one area to another, even if the areas are relatively close. Future surveys to assess potential anthropogenic disturbances in one specific area could be confounded if fluctuations in environmental conditions across time and space are not taken into consideration. The effect of *Study Area* became insignificant after adding environmental variables, thus providing evidence that the most important environmental gradients affecting the fish community were among those we measured, i.e., *Depth*, *Bottom temperature*, *Bottom salinity*, *Percent gravel*, *Percent mud, Latitude*, *Longitude*, and *Distance offshore*. Measuring and including these environmental variables in future investigations of potential disturbance will control for their confounding fluctuations across space and increase the power of any future before-after-control-impact (BACI) analyses designed to assess the suspected effects of a disturbance (Smith, 2002). The observed changes in the fish communities across two years are

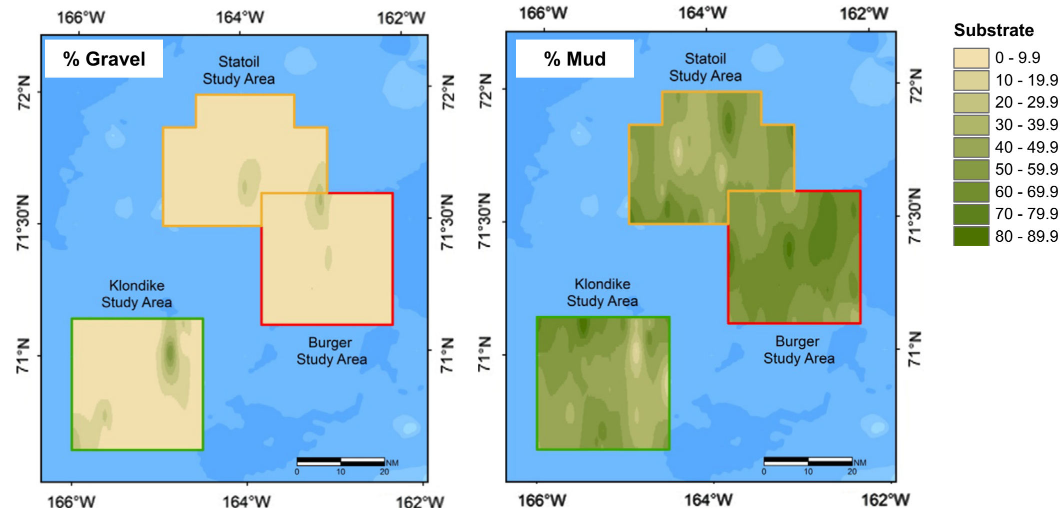

Fig. 11. Percentage of gravel and mud in sediment by study area from samples gathered 2008–2010 (data from Blanchard et al., https://workspace.aoos.org).

Table 4
Coefficients for the continuous variables estimated from the environmentally informed (EI) models of demersal fishes in the northeastern Chukchi Sea, which excluded study area and included eight continuous variables. Models are based on 2009–2010 collections with both bottom trawl gears.

Species	Distance								
		Depth	Offshore	Latitude	Longitude	Salinity	Temperature	Gravel	Mud
Species richness	Coef	−0.05	0.00	−0.63	0.27	0.44	0.10	0.00	0.01
	p	0.051	0.819	0.386	0.176	0.015	0.009	0.294	< 0.001
Total fish density	Coef	−0.12	0.02	−2.69	0.74	0.40	0.14	0.02	0.02
	p	0.009	0.127	0.055	0.038	0.199	0.087	0.014	< 0.001
Arctic cod	Coef	0.02	0.08	−6.15	1.87	−0.18	0.24	0.02	0.02
	p	0.759	< 0.001	0.004	< 0.001	0.689	0.021	0.035	0.002
Arctic staghorn sculpin	Coef	−0.48	0.02	−8.04	0.70	−0.55	−0.09	−0.02	0.02
	p	< 0.001	0.572	0.022	0.581	0.505	0.673	0.101	0.209
Canadian eelpout	Coef	0.08	0.04	0.12	0.82	1.91	0.23	−0.02	0.02
	p	0.469	0.257	0.969	0.264	0.014	0.137	0.111	0.054
Stout eelblenny	Coef	0.12	−0.01	3.04	−0.16	1.22	0.23	−0.04	0.01
	p	0.192	0.793	0.239	0.810	0.065	0.124	0.013	0.432
Bering flounder	Coef	0.22	0.02	0.61	−1.06	0.80	−0.11	−−0.04	−0.02
	p	0.142	0.743	0.872	0.462	0.472	0.619	0.041	0.372
Assemblage structure									
nMDS axis 1	Coef	0.03	< −0.01	0.87	−0.05	0.38	< −0.01	−0.01	< −0.01
	p	0.409	0.563	0.118	0.741	0.091	0.983	0.018	0.964
nMDS axis 2	Coef	−0.07	−0.01	−0.54	−0.07	0.07	−0.01	< −0.01	< −0.01
	p	0.010	0.066	0.257	0.590	0.732	0.777	0.459	0.674

problematic for assessing the potential effects of anthropogenic disturbance. This temporal variability will hinder the power of a BACI analysis if insufficient before and after years are sampled in relation to the suspected disturbance. Consistent use of one type of trawl that targets the appropriate size-spectra of fish would eliminate an important source of variation, the only one over which researchers have control.

5. Conclusions

This study shows small-scale spatial differences in fish communities in the northeastern Chukchi Sea. Contrary to our initial expectation, we were able to document heterogeneity in species richness, density and assemblage structure. Additionally indicator species from five dominant fish families are not similarly or uniformly distributed across the three study areas. The higher fish richness and density are explained by salinity, temperature, percent gravel and percent mud of the more southerly area. These physical characteristics of the area explain the erosional nature that influences the fish. The importance of this conclusion is to emphasize the inclusion of measurement of physical characteristics in all studies to control for their confounding fluctuations across even small spatial scales. The type of net used to capture the fish can be confounding and must also be considered. Though larger fishes were not collected by the small nets used, most were < 150 mm and are likely representative of the demersal fishes of the northeastern Chukchi Sea. Consistent collection methods for fishes and physical measurements are required now to detect future effects of a suspected climatological or anthropological disturbance.

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References

Alverson, D.L., Wilimovsky, N.J., 1966. Fishery investigations of the southeastern Chukchi Sea. In: Wilomovski, N.J., Wolfe, J.N. (Eds.), Environment of the Cape Thompson region, Alaska, U.S.. Atomic Energy Commission, Washington, District of Columbia, pp. 843–860.

Andriashev, A.P., 1954. Fishes of the Northern Seas of the USSR. Opredeiteli po Faune SSSR 53. Akademii Nauk SSSR, Moscow p. 567. [Translated from Russian: Israel Program for Scientific Translations, 1964, 617 pp.].

Arab, A., Wildhaber, M.L., Wikle, C.K., Gentry, C.N., 2008. Zero-inflated modeling of fish catch per unit area resulting from multiple gears: application to channel catfish and shovelnose sturgeon in the Missouri River. North American Journal of Fisheries Management 28, 1044–1058.

Barber, W.E., Smith, R.L., Vallarino, J., Meyer, R.M., 1997. Demersal fish assemblages of the northeastern Chukchi Sea, Alaska. Fishery Bulletin 95, 195–209.

Barber, W.E., Smith, R.L., Weingartner, T.J., 1994. Fisheries Oceanography of the Northeast Chukchi Sea: Final Report. US Department of the Interior, Minerals Management Service, Anchorage, Alaska, OCS Study MMS-93-0051, 101 pp.

Blanchard, A.L., Parris, C.L., Knowlton, A.L., Wade, N.R., 2013a. Benthic ecology of the northeastern Chukchi Sea. Part I. Environmental characteristics and macro faunal community structure 2008–2010. Continental Shelf Research 67, 52–66.

Blanchard, A.L., Parris, C.L., Knowlton, A.L., Wade, N.R., 2013b. Benthic ecology of the northeastern Chukchi Sea. Part II: Spatial variation of megafaunal community structure, 2009–2010. Continental Shelf Research 67, 67–76.

Bluhm, B.A., Gradinger, R., 2008. Regional variability in food availability for Arctic marine mammals. Ecological Applications 18 (Supplement S77–S96).

Burnham, K.P., Anderson, D.R., 2002. Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach, second ed.. Springer–Verlag, New York p. 488.

Cohen, D.M., Inada, T., Iwamoto, T., Scialabba, N., 1990. FAO Species Catalogue. Vol. 10. Gadiform Fishes of the World (Order Gadiformes). An Annotated and Illustrated Catalogue of Cods, Hakes, Grenadiers and other Gadiform Fishes Known to Date. FAO Fisheries Synopsis 125, Rome, 442 pp.

Day, R.H., Weingartner, T.J., Hopcroft, R.R., Aerts, L.A.M., Blanchard, A.L., Gall, A.E., Gallaway, B.J., Hannay, D.E., Holladay, B.A., Mathis, J.T., Norcross, B.L., Questel, J. M., Wisdom, S.S., 2013. The offshore northeastern Chukchi Sea, Alaska: a complex high-latitude system. Continental Shelf Research 67, 147–165.

Eastman, J.T. Comparison of the Antarctic and Arctic fish faunas. Cybium 21, 1997, 335–352.

Edenfield, L.E., Norcross, B.L., Carroll, S.S., Holladay, B.A., 2011. Chapter 5: Trophic Relationships of Five Species of Demersal Fishes in the Northeastern Chukchi Sea, 2009–2010. In: A Synthesis of Diversity, Distribution, Abundance, Age, Size, and Diet of Fishes in the Lease Sale 193 Area of the Northeastern Chukchi Sea. Final Report. ConocoPhillips Alaska, Inc., Shell Exploration & Production Company, and StatOil USA E&P, Inc., Anchorage, Alaska, 48 pp.

Eisner, L., Hillgruber, N., Martinson, E., Maselko, J., 2013. Pelagic fish and zooplankton species assemblages in relation to water mass characteristics in the northern Bering and southeast Chukchi seas. Polar Biology 36, 87–113.

Frost, K.J., Lowry, L.F., 1980. Feeding of ribbon seals (*Phoca fasciata*) in the Bering Sea in spring. Canadian Journal of Zoology 58, 1601–1607.

Frost, K.J., Lowry, L.F., 1983. Demersal Fishes and Invertebrates Trawled in the Northeastern Chukchi and Western Beaufort Seas 1976–1977. U.S. Dep. of Commerce, NOAA Technical Report NMFS-SSRF-764, 22 pp.

Gelwick, F.P., 1990. Longitudinal and temporal comparisons of riffle and pool fish assemblages in a northeastern Oklahoma Ozark stream. Copeia 1990, 1072–1082.

Grebmeier, J.M., Overland, J.E., Moore, S.E., Farley, E.V., Carmack, E.C., Cooper, L.W., Frey, K.E., Helle, J.H., McLaughlin, F.A., McNutt, S.L., 2006. A major ecosystem shift in the Northern Bering Sea. Science 311, 1461–1464.

Gunderson, D.R., Ellis, I.E., 1986. Development of a plumb staff beam trawl for sampling demersal fauna. Fisheries Research 4, 35–41.

Hillebrand, H., 2004. On the generality of the latitudinal diversity gradient. The American Naturalist 163, 192–211.

Johnson, L., 1997. Living with uncertainty. In: Reynolds, J.S. (Ed.), Fish Ecology in Arctic North America. American Fisheries Society Symposium 19, Bethesda, Maryland, pp. 340–345.

Kruskal, J.B., 1964. Multidimensional scaling by optimizing goodness of fit to a nonmetric hypothesis. Psychometrika 291, 1–27.

Lobo, J.M., Martin-Piera, F., 2002. Searching for a predictive model for species richness of Iberian dung beetle based on spatial and environmental variables. Conservation Biology 16, 158–173.

Logerwell, E.A., Rand, K., Parker-Stetter, S., Horne, J., Weingartner, T., Bluhm, B., 2010. Beaufort Sea Marine Fish Monitoring 2008: Pilot Survey and Test of Hypotheses—Final Report. U.S. Department of the Interior, Minerals Management Service, Alaska OCS Region, Anchorage, Alaska, BOEMRE-2010-048, 262 pp.

Lowry, L.F., Frost, K.J., 1981. Distribution, growth, and foods of Arctic cod (*Boreogadus saida*) in the Bering, Chukchi, and Beaufort seas. Canadian Field-Naturalist 95, 186–191.

Manzer, J.I., Shepard, M.P., 1962. Marine survival, distribution, and migration of pink salmon off the British Columbia coast. In: Wilimovsky, N.J. (Ed.), Symposium on Pink Salmon. MacMillian Lectures in Fisheries. Institute of Fisheries, University of British Columbia, Vancouver, pp. 113–122.

Matarese, A.C., Kendall_Jr, A.W., Blood, D.M., Vinter, B.M., 1989. Laboratory Guide to Early Life History of Northeast Pacific fishes. NOAA Technical Report NMFS 80, Seattle, Washington, 652 pp.

Matthews, W.J., 1987. Geographic variation in *Cyprinella lutrensis* (Pisces: Cyprinidae) in the United States, with notes on *Cyprinella lepida*. Copeia 1987, 661 – 637.

McCune, B., Mefford, M.J., 2006. Multivariate Analysis of Ecological Data, version 5.31. MjM Software. Gleneden Beach, Oregon.

Mecklenburg, C.W., Mecklenburg, T.A., 2011. Fish, in: Arctic Ocean Diversity, ⟨http://www.arcodiv.org/fish.html⟩ 10 January 2012.

Mecklenburg, C.W., Mecklenburg, T.A., Thorsteinson, K.L., 2002. Fishes of Alaska. American Fisheries Society, Bethesda, Maryland p. 1037.

Mecklenburg, C.W., Møller, P.R., Steinke, D., 2011. Biodiversity of arctic marine fishes: taxonomy and zoogeography. Marine Biodiversity 41, 109–140 +online resources 1–5.

Mecklenburg, C.W., Norcross, B.L., Holladay, B.A., Mecklenburg, T.A., 2008. Fishes. In: Hopcroft, R., Bluhm, B., Gradinger, R. (Eds.), Arctic Ocean Synthesis: Analysis of Climate Change Impacts in the Chukchi and Beaufort Seas with Strategies for Future Research. North Pacific Research Board, Anchorage, Alaska, pp. 66–79.

Mecklenburg, C.W., Stein, D.L., Sheiko, B.A., Chernova, N.V., Mecklenburg, T.A., Holladay, B.A., 2007. Russian-American long-term census of the Arctic: benthic fishes trawled in the Chukchi Sea and Bering Strait, August 2004. Northwestern Naturalist 88, 168–187.

Minami, M., Lennert-Cody, C.E., Gao, W., Roman-Verdesoto, M., 2007. Modeling shark bycatch: the zero-inflated negative binomial regression model with smoothing. Fisheries Research 84, 210–221.

Nelson, J.S., Crossman, E.J., Espinosa-Pérez, H., Lindley, L.T., Gilbert, C.R., Lea, R.N., Williams, J.D., 2004. Common and Scientific Names of Fishes from the United States, Canada, and Mexico, sixth ed.. American Fisheries Society Special Publication 29, Bethesda, Maryland p. 386.

North Pacific Fisheries Management Council (NPFMC), 2009. Arctic FMP, ⟨http://www.fakr.noaa.gov/npfmc/PDFdocuments/fmp/Arctic/ArcticFMP⟩, 1 May 2012.

Norcross, B.L., Holladay, B.A., Edenfield, L.E., 2011a. 2009 Environmental Studies Program in the Chukchi Sea: Fisheries Ecology of the Burger and Klondike Survey Areas. Annual Report to ConocoPhillips and Shell Exploration & Production Company, Anchorage, Alaska, 56 pp.

Norcross, B.L., Holladay, B.A., Gleason, C., 2011b. Chapter 4: Length–weight–age Relationships of Demersal Fishes in the Chukchi Sea. In: A Synthesis of Diversity, Distribution, Abundance, Age, Size, and Diet of Fishes in the Lease Sale 193 Area of the Northeastern Chukchi Sea. Final Report. ConocoPhillips Alaska, Inc., Shell Exploration & Production Company, and StatOil USA E&P, Inc., Anchorage, Alaska, 30 pp.

Norcross, B.L., Holladay, B.A., Mecklenburg, C.W., 2013. Recent and Historical Distribution and Ecology of Demersal Fishes in the Chukchi Sea Planning Area. Final Report to the Bureau of Ocean Energy Management, Alaska OCS Region, Anchorage, Alaska, 200 pp.

Norcross, B.L., Holladay, B.A., Müter, F.-J., 1995. Nursery area characteristics of pleuronectids in coastal Alaska, USA. Netherlands Journal of Sea Research 34, 161–175.

O'Hara, R.B., 2005. Species richness estimators: how many species can dance on the head of a pin? Journal of Animal Ecology 74, 375–386.

Piatt, J.F., Wells, J.L., MacCharles, A., Fadely, B., 1990. The distribution of seabirds and their prey in relation to ocean currents in the southeastern Chukchi Sea. Canadian Wildlife Service Occasional Papers 68, 21–31.

Power, G., 1997. A review of fish ecology in Arctic North America. In: Reynolds, J.B. (Ed.), Fish Ecology in Arctic North America. American Fisheries Society Symposium 19, Bethesda, Maryland, pp. 13–39.

Power, J.H., Moser, E.B., 1999. Linear model analysis of net catch data using the negative binomial distribution. Canadian Journal of Fisheries and Aquatic Sciences 56, 191–200.

Pruter, A.T., Alverson, D.L., 1962. Abundance, distribution and growth of flounders in the southeastern Chukchi Sea. Journal du Conseil International pour l'Exploration de la Mer 27, 81–99.

Questel, J.M., Clarke, C., Hopcroft, R.R., 2013. Seasonal and interannual variation in the planktonic communities of the northeastern Chukchi Sea during the summer and early fall. Continental Shelf Research 67, 23–41.

Raborn, S.W., Gallaway, B.J., Cole, J.G., Gazey, W.J., 2011. Effects of turtle excluder devices (TEDs) on the bycatch of the blacknose shark in the Gulf of Mexico penaeid shrimp fishery. North American Journal of Fisheries Management 32, 333–345.

Raborn, S.W., Will, T., Miranda, L.E., 2001. An assessment of larval fish density and assemblage structure within mid-channel and backwater habitats in a Mississippi stream. Journal of Freshwater Ecology 16, 395–401.

Rohde, K., 1992. Latitudinal gradients in species diversity: the search for the primary cause. Oikos 65, 514–527.

Shono, H., 2008. Application of the Tweedie distribution to zero-catch data in CPUE analysis. Fisheries Research 93, 154–162.

Smith, R.L., Vallarino, M., Barbour, E., Fitzpatrick, E., Barber, W.E., 1997a. Population biology of the Bering flounder in the northeastern Chukchi Sea. In: Reynolds, J. (Ed.), Fish Ecology in Arctic North America. American Fisheries Society Symposium 19, Bethesda, Maryland, pp. 127–132.

Smith, R.L., Barber, W.E., Vallarino, M., Gillispie, J., Ritchie, A., 1997b. Population biology of the Arctic staghorn sculpin in the northeastern Chukchi Sea. In: Reynolds, J. (Ed.), Fish Ecology in Arctic North America. American Fisheries Society Symposium 19, Bethesda, Maryland, pp. 133–139.

Smith, E.P., 2002. BACI design. Encyclopedia of Environmetrics. John Wiley & Sons, Ltd., Chichester, UK, pp. 141–148.

Terceiro, M., 2003. The statistical properties of recreational catch rate data for some fish stocks of the northeast U.S. coast. Fishery Bulletin 101, 653–672.

Weingartner, T., Dobbins, E., Danielson, S., Potter, R., Statscewich, H., Winsor, P., 2013. Hydrographic variability of the northeastern Chukchi Sea shelf in summer-fall 2008–2010. Continental Shelf Research 67, 5–22.

Weingartner, T., Shimada, K., McLaughlin, F., Proshutinsky, A., 2008. Physical oceanography. In: Hopcroft, R., Bluhm, B., Gradinger, R. (Eds.), Arctic Ocean Synthesis: Analysis of Climate Change Impacts in the Chukchi and Beaufort Seas, with Strategies for Future Research. Final Report to the North Pacific Research Board, Anchorage, Alaska, pp. 6–17.

Willig, M.R., Kaufmann, D.M., Stevens, R.D., 2003. Latitudinal gradients of biodiversity: pattern, process, scale and synthesis. Annual Review Ecology and Systematics 34, 273–309.

Wyllie-Echeverria, T., Barber, W.E., Wyllie-Echeverria, S., 1997. Water masses and transport of age-0 Arctic Cod and age-0 Bering flounder into the northeastern Chukchi Sea. In: Reynolds, J. (Ed.), Fish Ecology in Arctic North America. American Fisheries Society Symposium 19, Bethesda, Maryland, pp. 60–67.

Zeller, D., Booth, S., Pakhomov, E., Swartz, W., Pauly, D., 2011. Arctic fisheries catches in Russia, USA, and Canada: baselines for neglected ecosystems. Polar Biology 34, 955–973.